Erzeugung und Anwendung ultrakurzer Laserpulse

Generation and Application of Ultrashort Laser Pulses

Prof. Ursula Keller

ETH Zurich, Switzerland

Festvortrag zur akademischen Feier aus Anlass der erstmaligen Verleihung des Young Researcher Award
Erlangen Graduate School in Advanced Optical Technologies
7. Januar 2008

Keller group: Thank you …

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

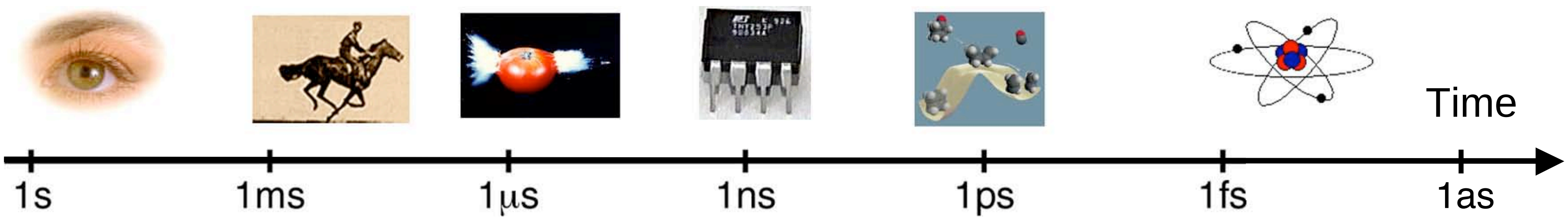
Ultrafast solid-state lasers: High pulse repetition rate
Max Stumpf, Andreas Oehler, Selina Pekarek, Dr. Thomas Südmeyer

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

MBE and MOVPE growth in ETH clean room facility (FIRST-lab)
Dr. Matthias Golling
ETH FIRST Lab staff: Dr. Silke Schön (MBE), Dr. Emilio Gini (MOVPE)

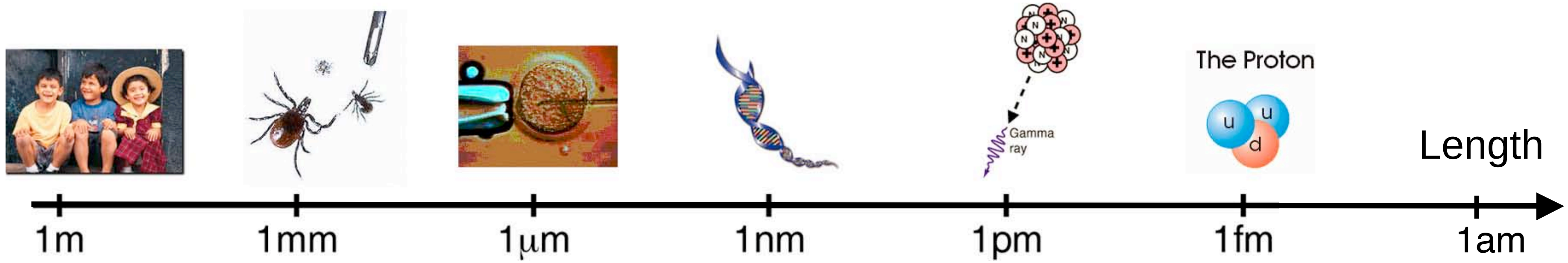
High field laser physics, attosecond pulse generation and science
Dr. Lukas Gallmann, Dr. Amelle Zair, Dr. Claudio Cirelli
Christian Erny, Petrissa Eckle, Mirko Holler, Florian Schlapper, Matthias Weger

Ultrafast laser physics (ULP)



1 femtosecond = 1 fs = 10^{-15} s

1 attosecond = 1 as = 10^{-18} s



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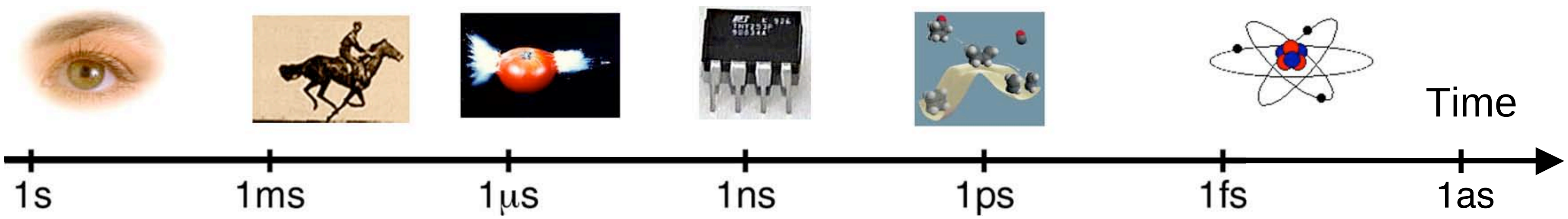

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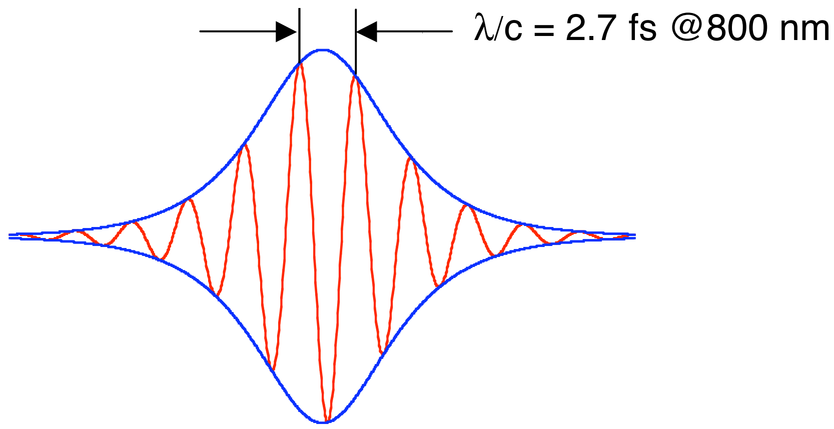
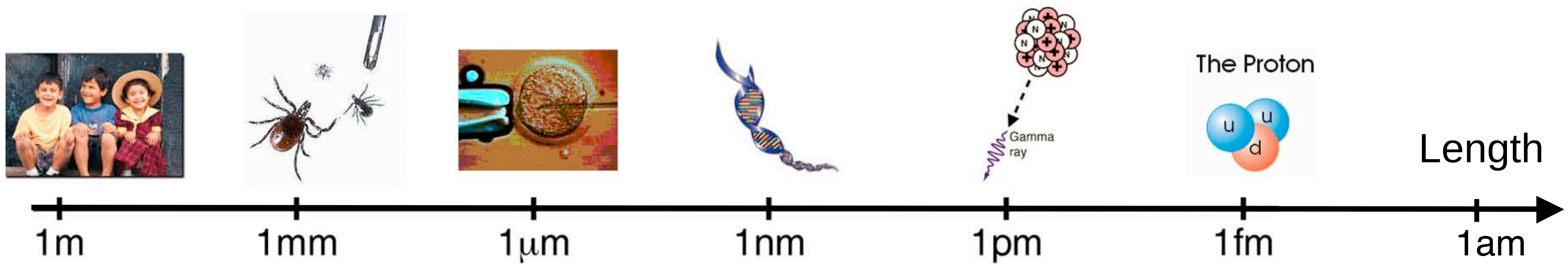
Pulse generation directly from laser oscillators:
milliseconds to femtosecond regime





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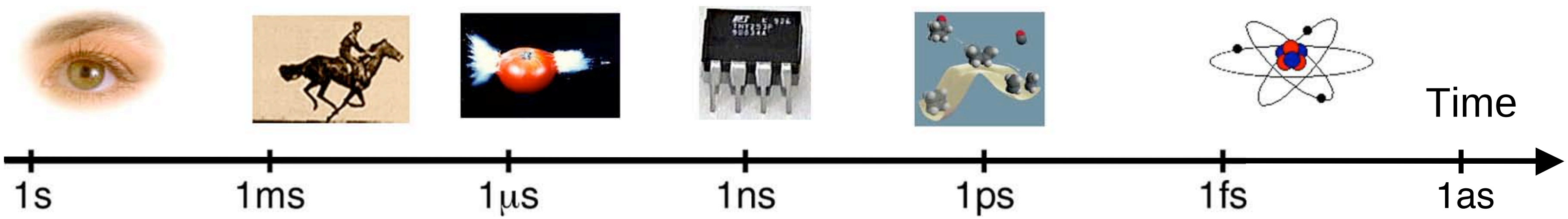

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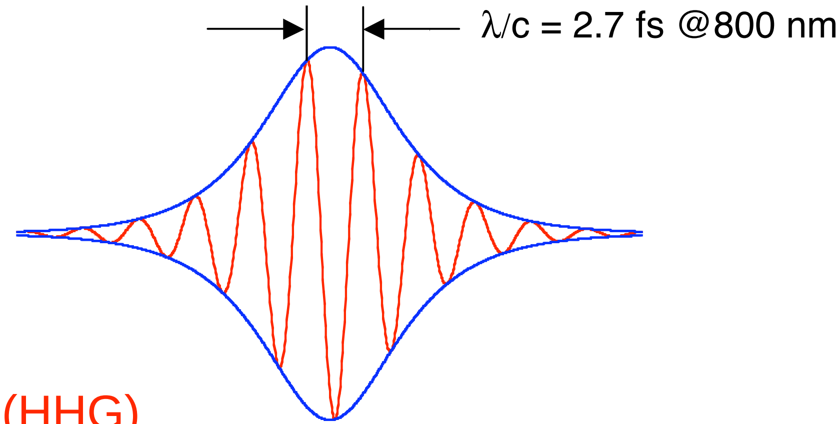
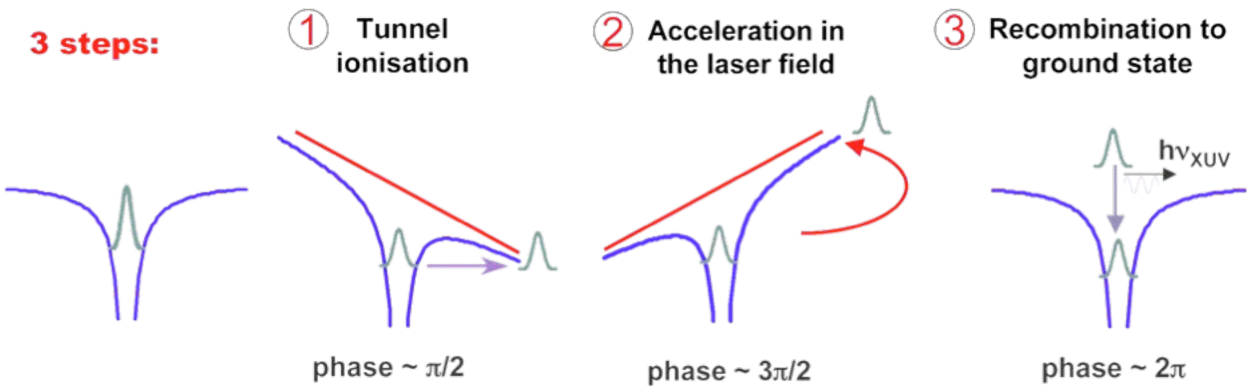
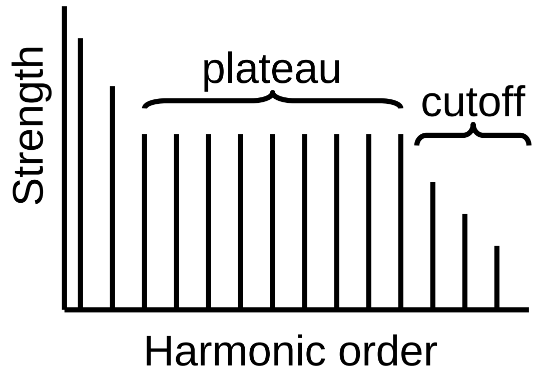


Pulse generation directly from laser oscillators: milliseconds to femtosecond regime

Attosecond regime: High Harmonic Generation (HHG)

VUV to soft-X-ray regime





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)

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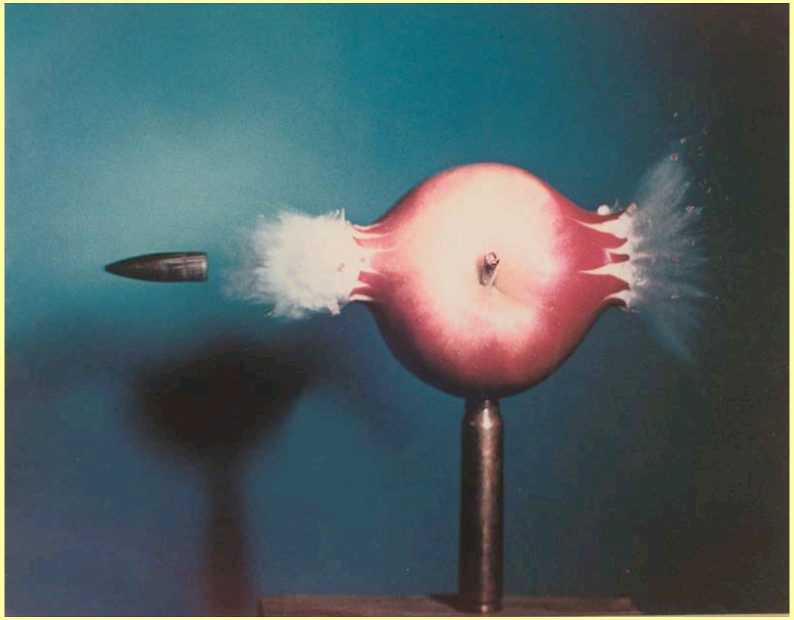
Time resolution limited by pulse duration

similar to flash photography:



Triggered flash lamps for ≈1 μs exposure time
1964 by Harold E. Edgerton, MIT

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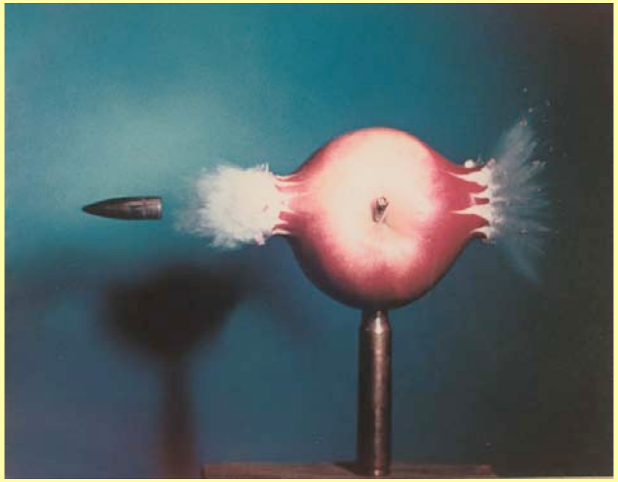
  measurements of fast processes

Time resolution limited by pulse duration (e.g. flash photography)
Harold E. Edgerton, MIT



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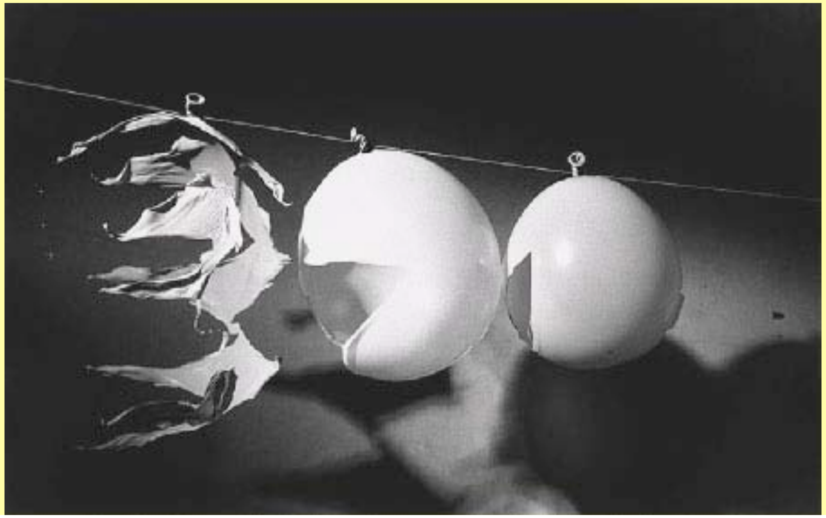

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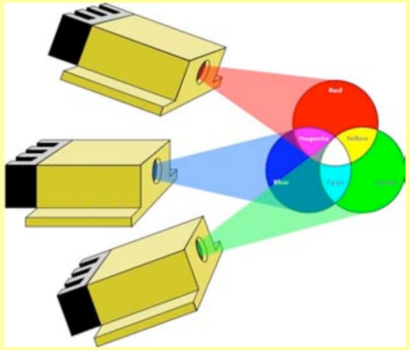
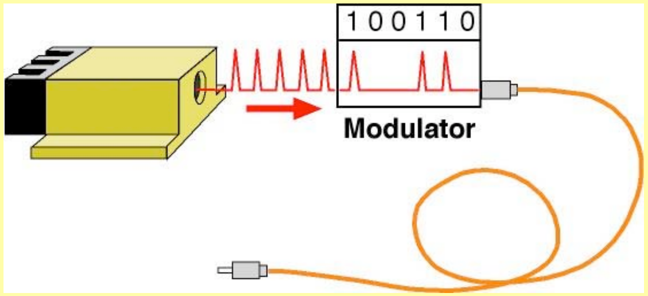
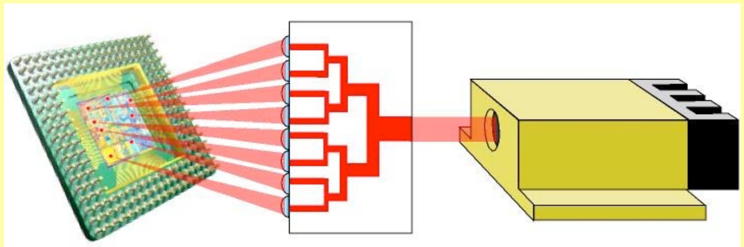
Laser display (RGB source):



Optical communication:



Optical clocking and interconnects:



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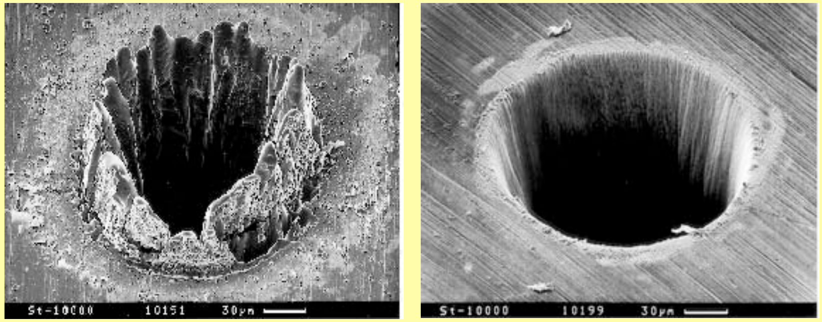
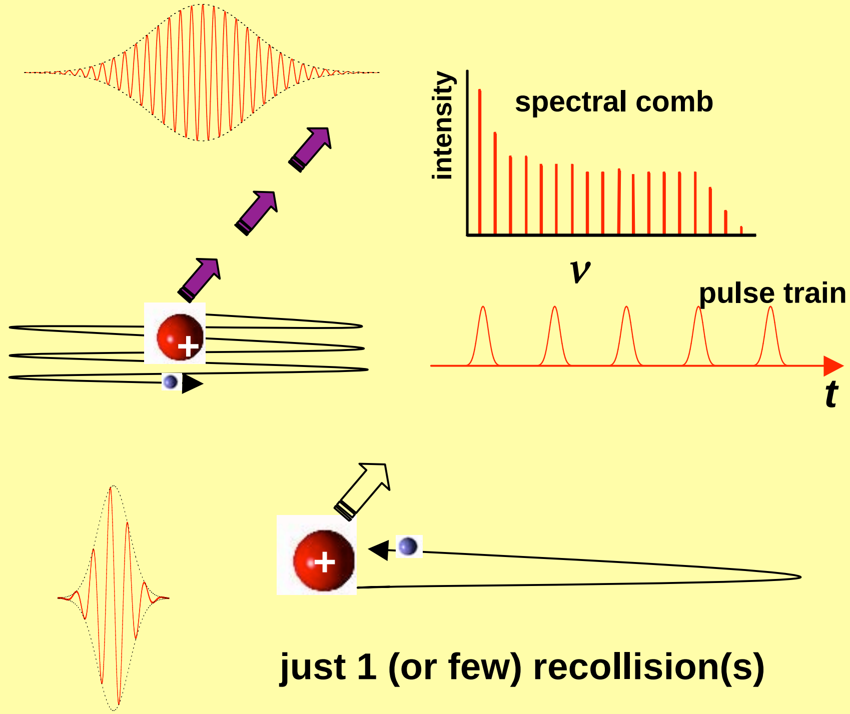
Precise material processing:



High field physics: attosecond science



Applications of ultrafast lasers

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  measurements of fast processes

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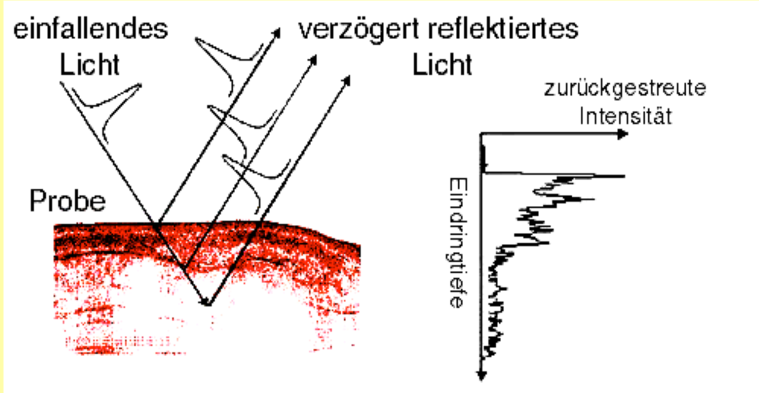
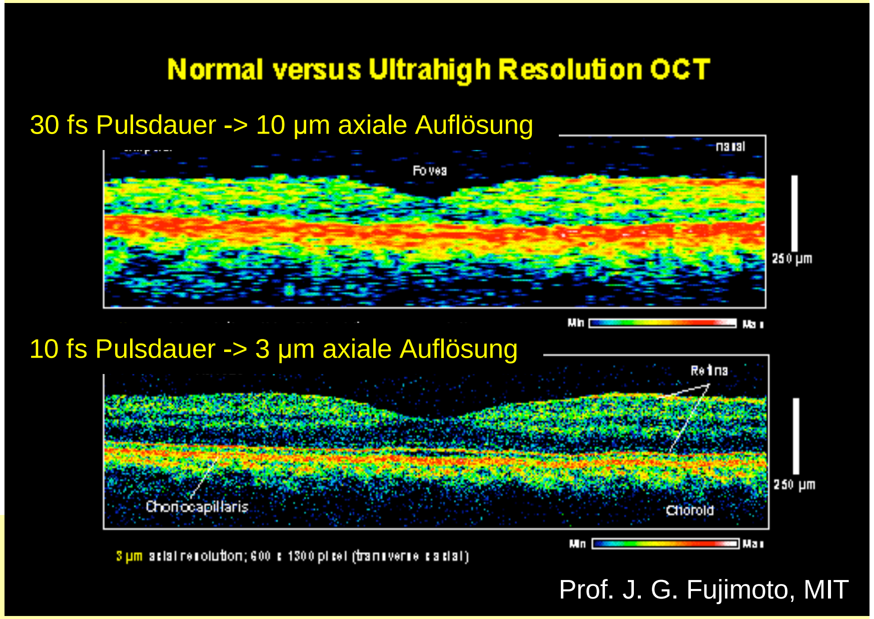
OCT:





OCT image of retina (around fovea)
Early detection of retinal detachment

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Optical clock (>100 THz):

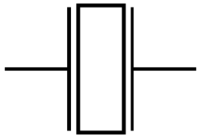
- time is defined by a certain number of oscillations within a given time interval: „the higher the frequency the more accurately the time interval is defined“

- **0.001 Hz**: Sand clock

- **1 Hz**: Mechanical clock

- **10 MHz**: Quartz oscillator

Piezoelectric crystal resonator



- **9 GHz**: Atomic clock

GPS

Applications of ultrafast lasers

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  measurements of fast processes

- **High pulse repetition rates**

  optical communication
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- **Broad optical spectrum**

  frequency metrology (frequency comb)
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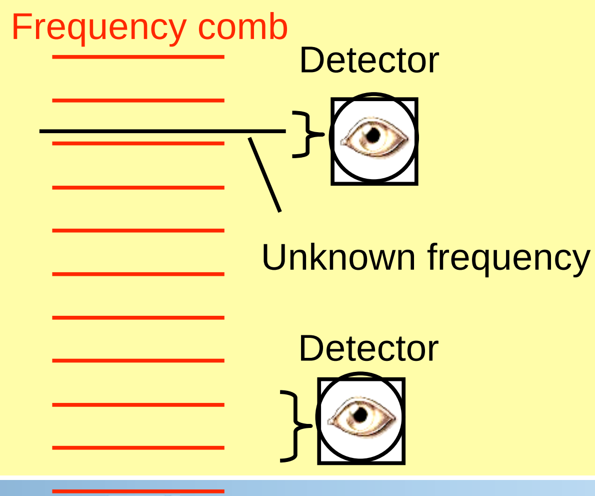
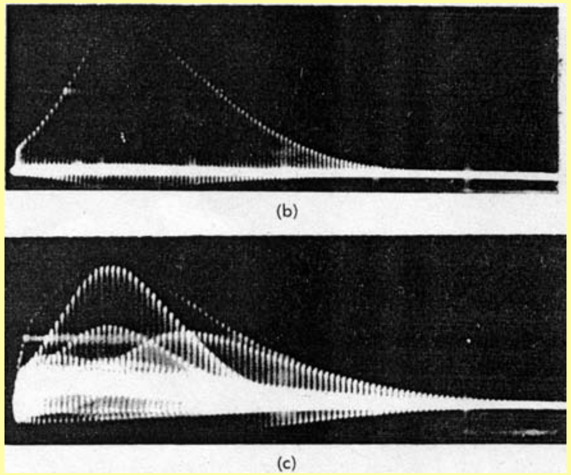
Optical clock (>100 THz):

- time is defined by a certain number of oscillations per fixed time interval: „higher frequency more accurate clock“
- optical frequency: too high for counting
- frequency comb of ultrafast laser: detector measures the difference in frequency = beating signal
- beating signal measures the „distance“ of unknown frequency to the lines in the frequency comb
- optical frequency becomes measurable
- Potential measurements: „are fundamental constants constant?“



Ultrashort pulse generation with modelocking

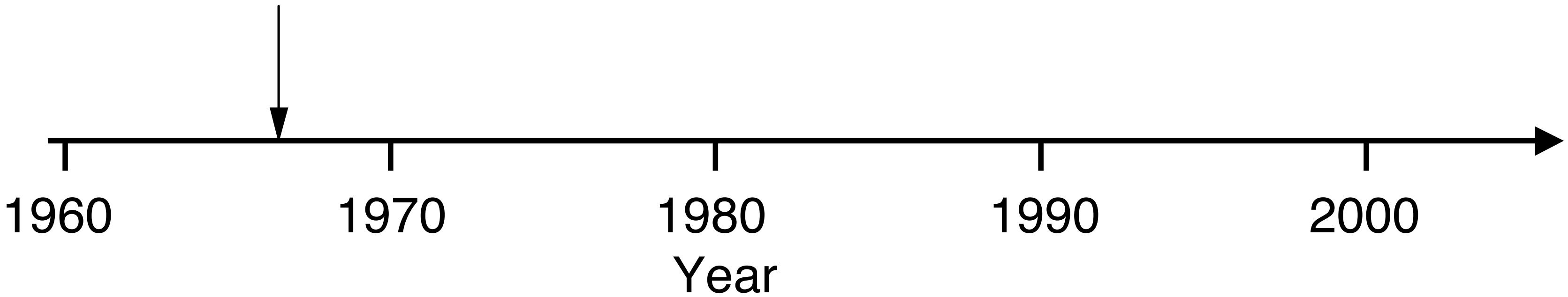
A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



200 ns/div

50 ns/div

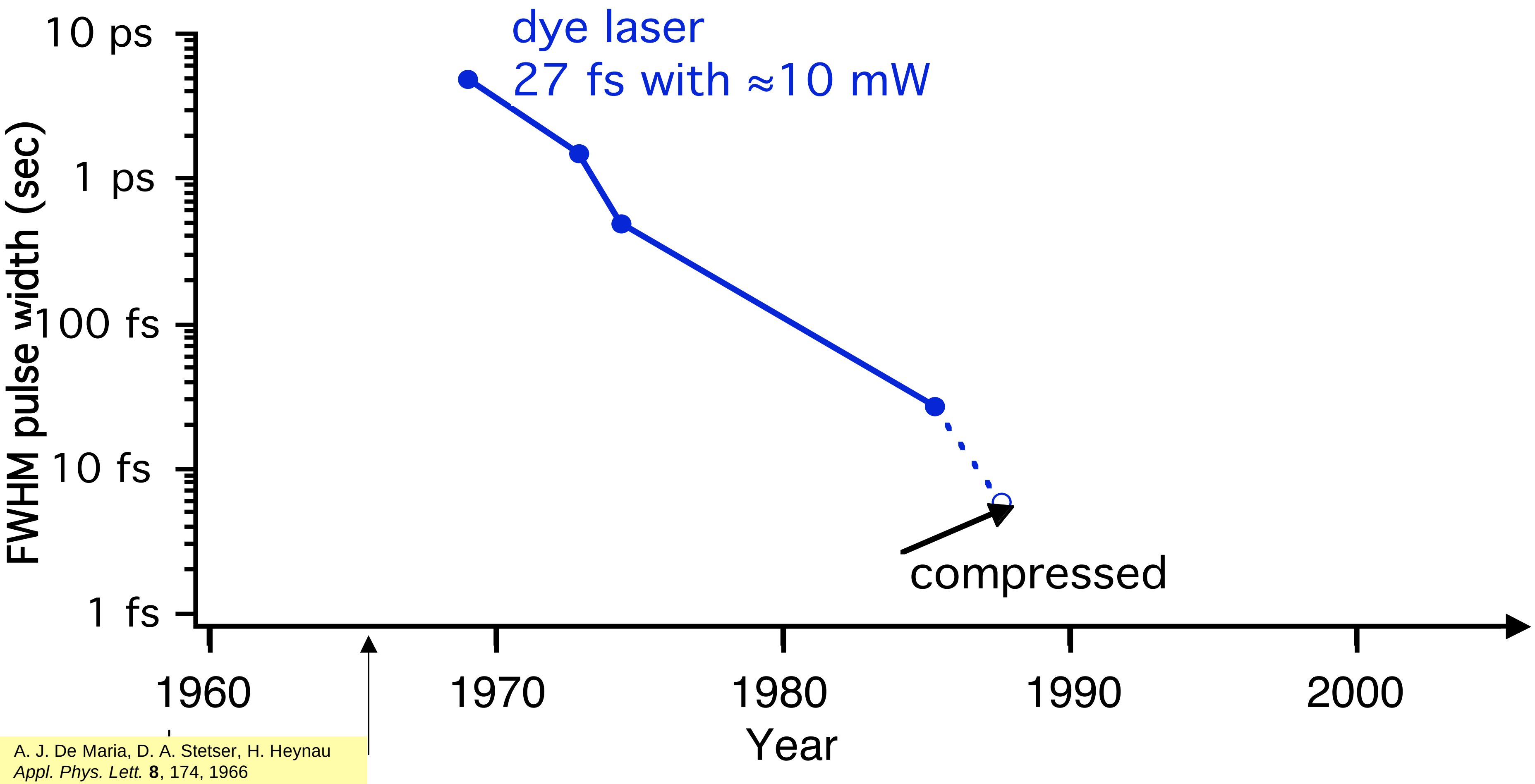
Nd:glass
first passively modelocked laser
Q-switched modelocked



Flashlamp-pumped solid-state lasers

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

Ultrashort pulse generation with modelocking



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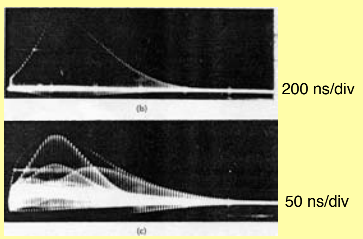


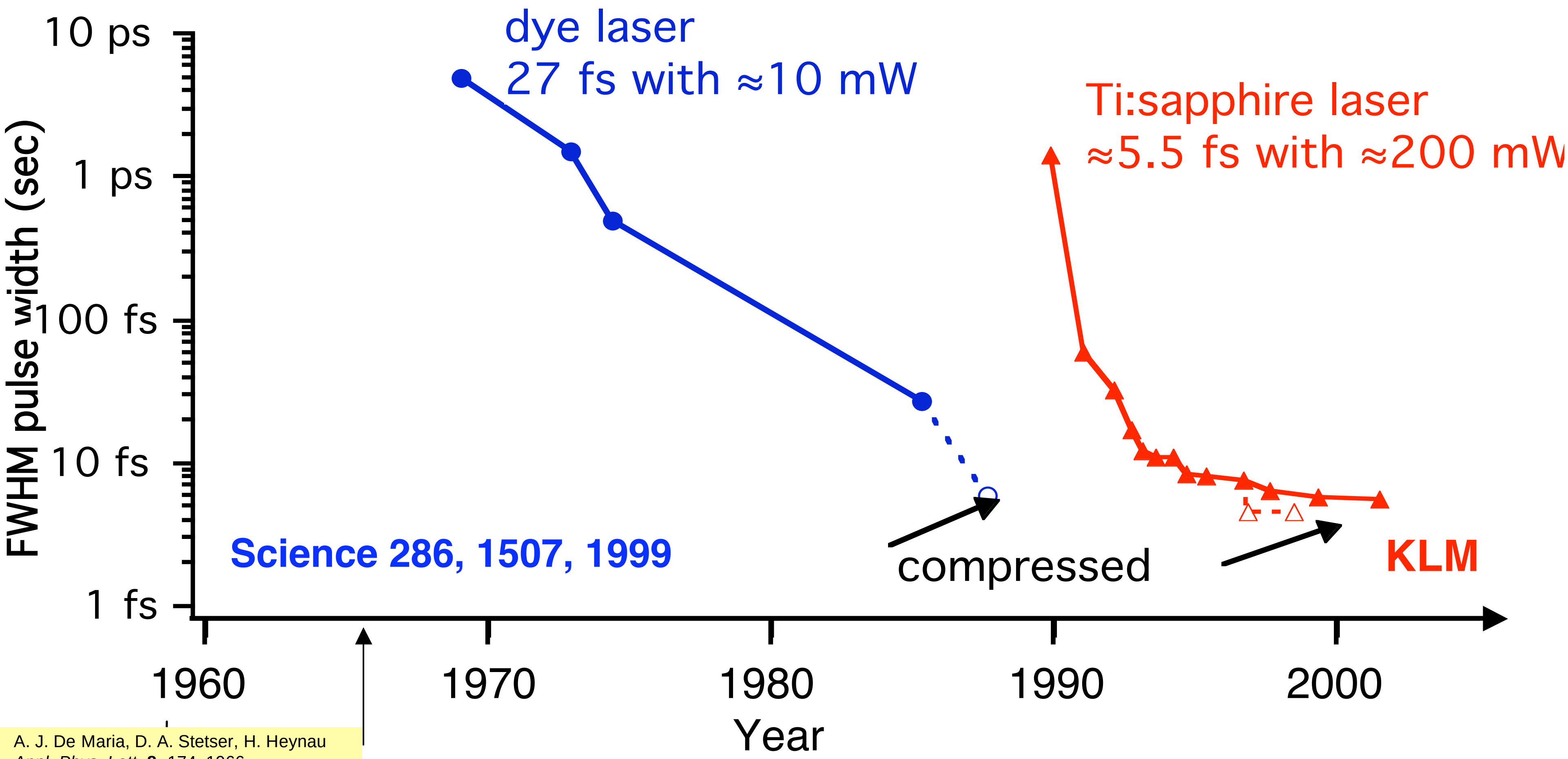
Nd:glass
first passively modelocked laser
Q-switched modelocked

E. P. Ippen, C. V. Shank et al, *Appl. Phys. Lett.* 21, 348, 1972

J. A. Valdmanis et al., *Opt. Lett.* 10, 131, 1985 (27 fs)

R. L. Fork et al., *Opt. Lett.* 12, 483, 1987 (6 fs)

Ultrashort pulse generation with modelocking



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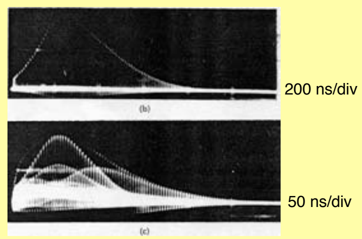


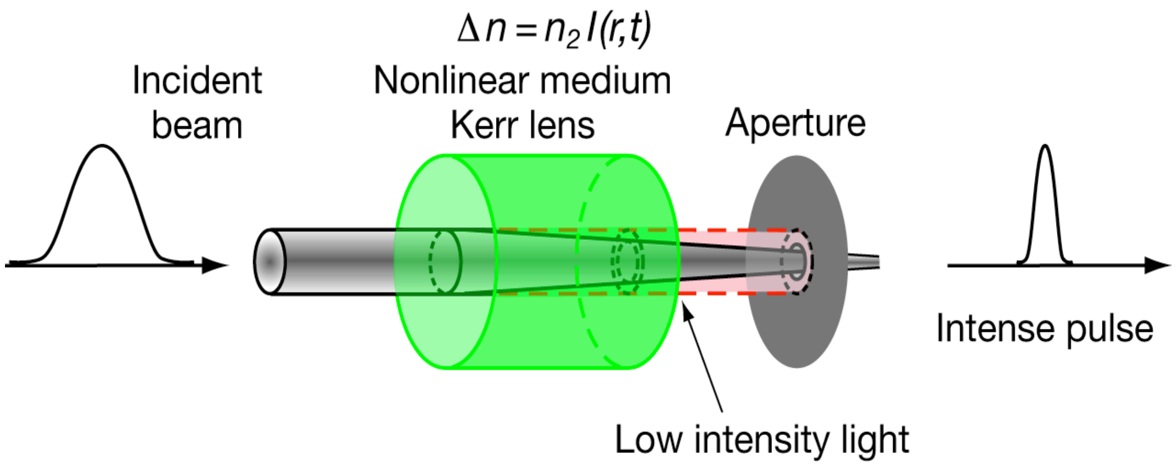
Nd:glass
first passively modelocked laser
Q-switched modelocked

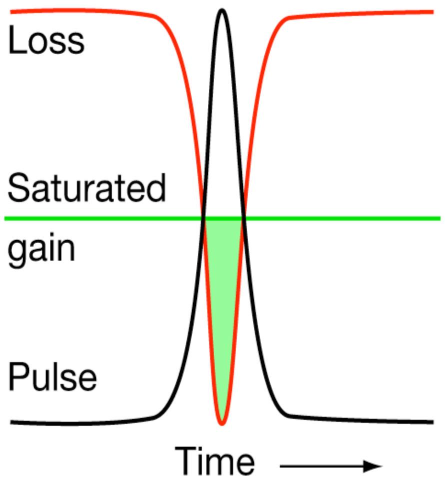
Kerr lens modelocking (KLM):

D. E. Spence, P. N. Kean, W. Sibbett, *Opt. Lett.* 16, 42, 1991

Kerr Lens Modelocking (KLM)

First Demonstration: D. E. Spence, P. N. Kean, W. Sibbett, *Optics Lett.* **16**, 42, 1991
Explanation: U. Keller et al., *Optics Lett.* **16**, 1022, 1991





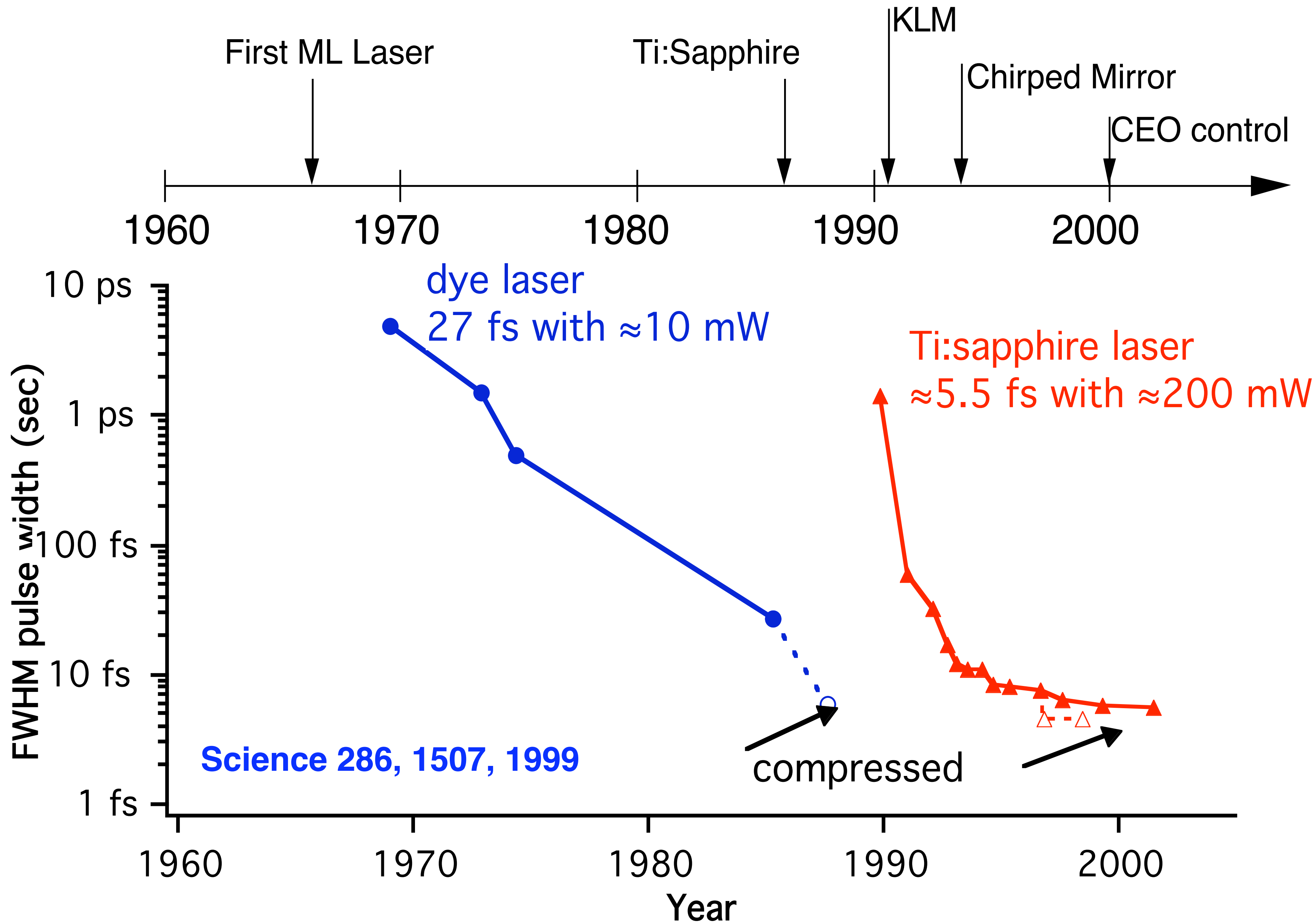
Advantages of KLM

- very fast thus shortest pulses
- very broadband thus broader tunability

Disadvantages of KLM

- not self-starting
- critical cavity adjustments (operated close to the stability limit)
- saturable absorber coupled to cavity design (limited application)

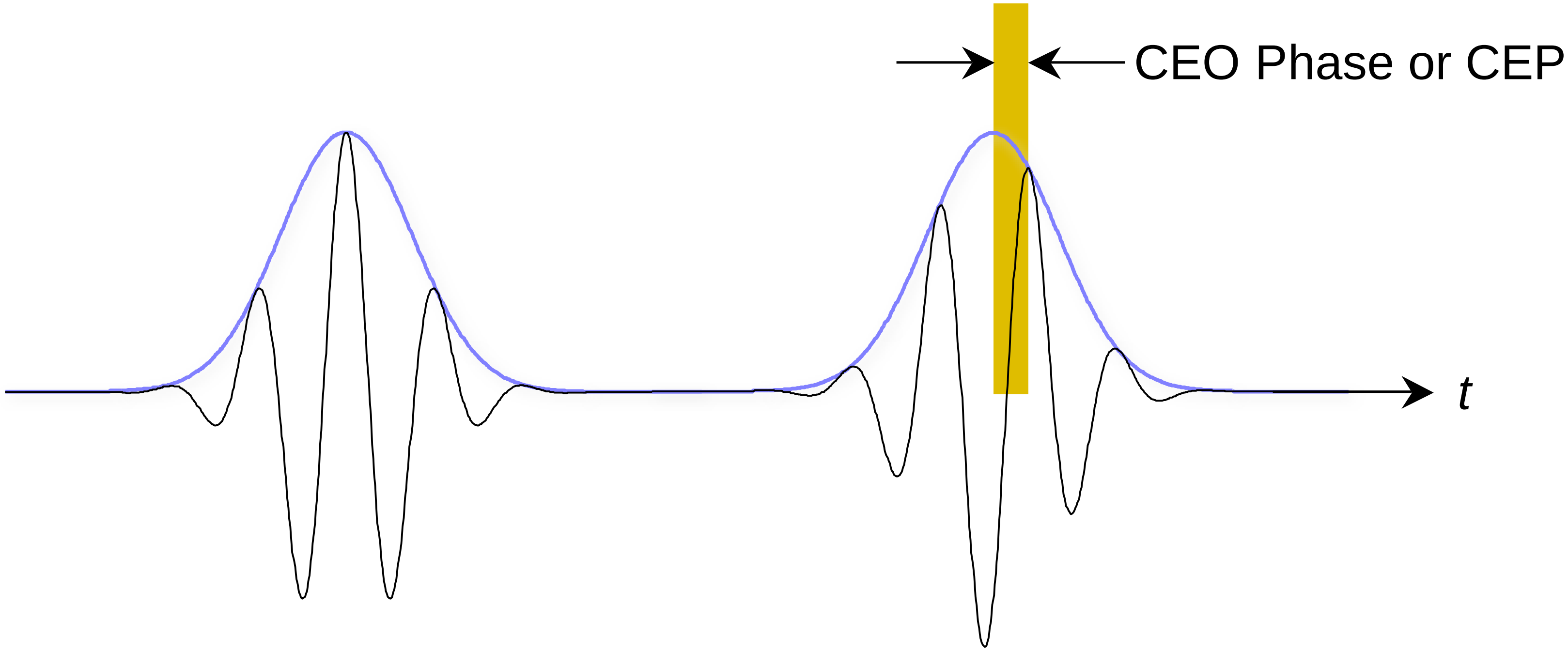
Frontier: Ultrashort pulse generation



Carrier-Envelope Offset (CEO) Phase

H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller
Appl. Phys. B **69**, 327 (1999)

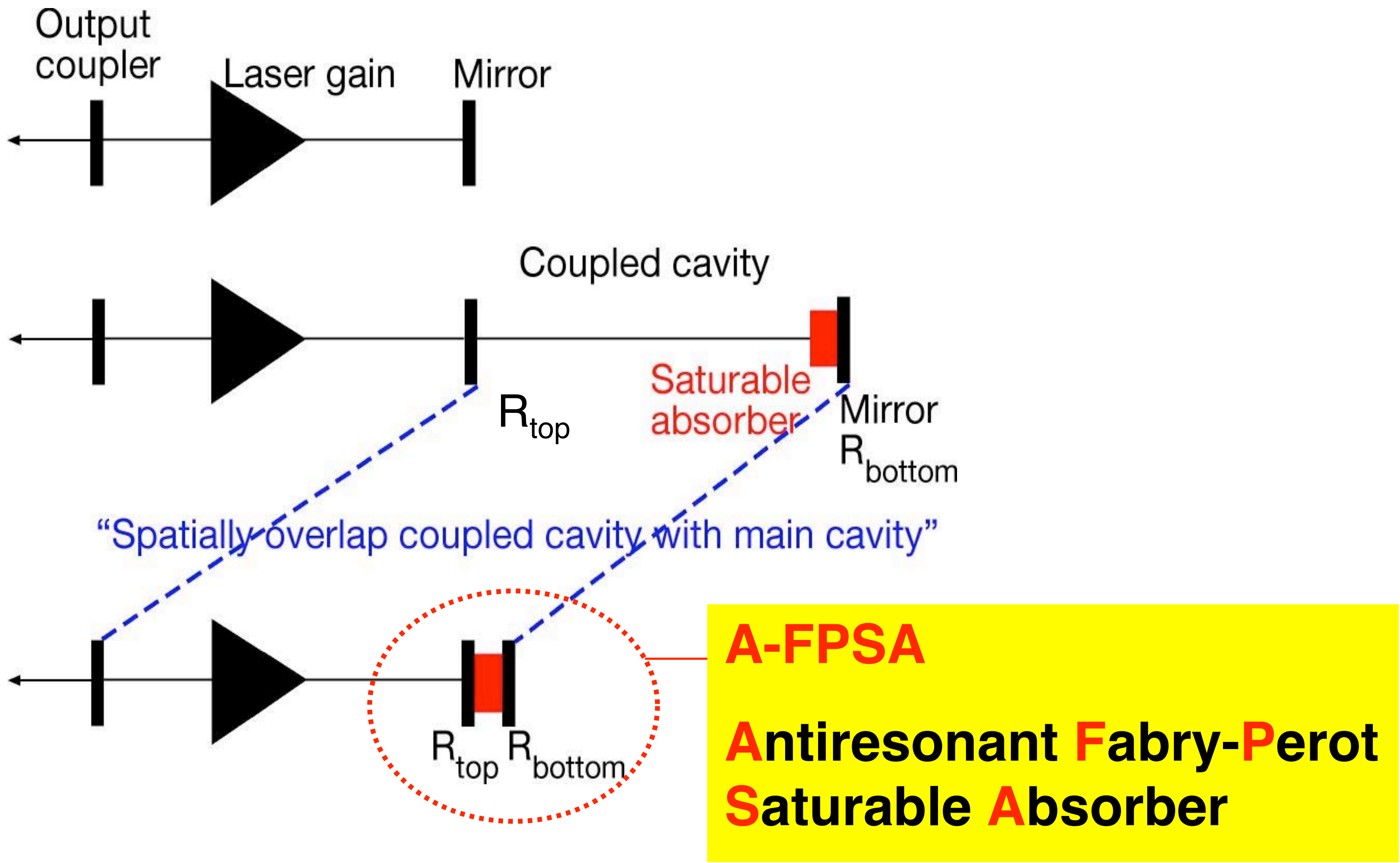
Mode-locked Pulse Train



Controlled in laser oscillator

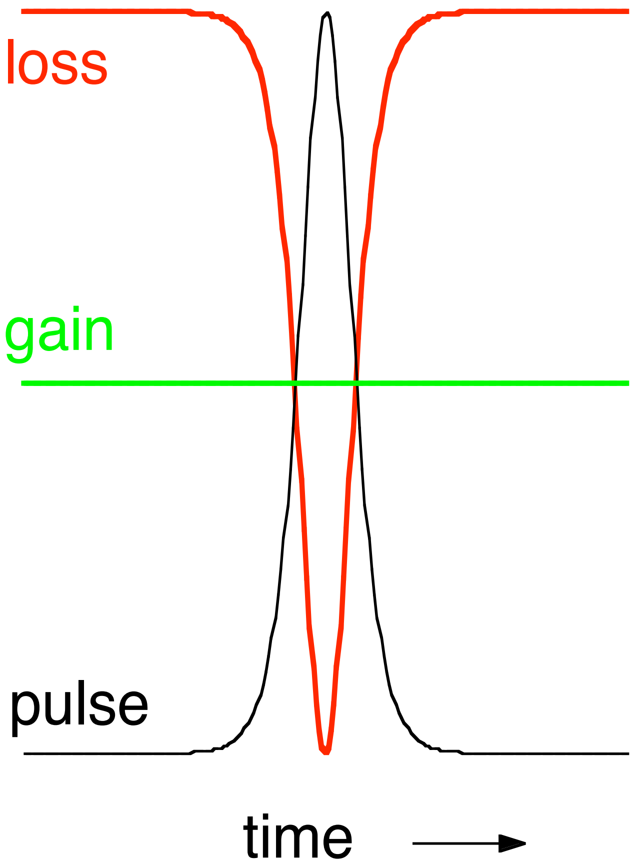
Historical evolution for SESAMs

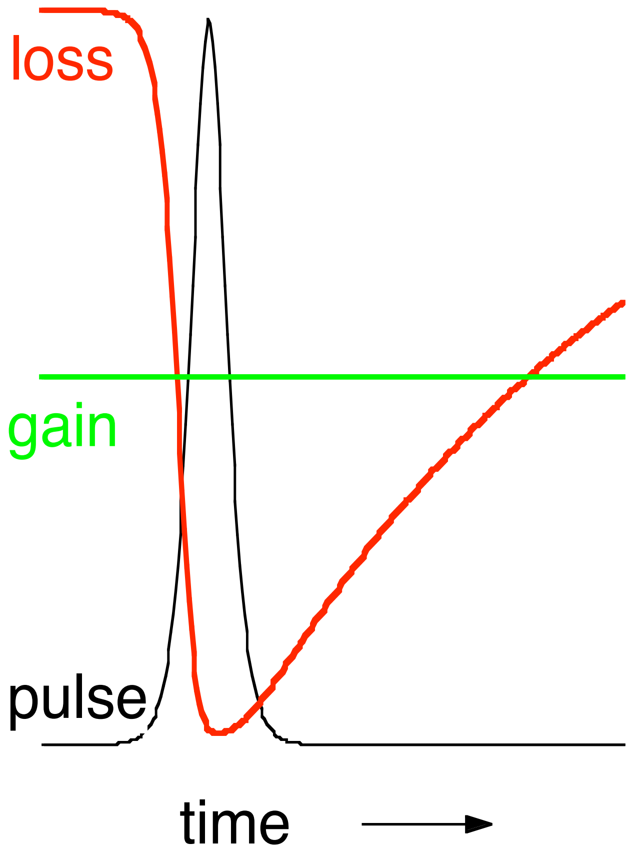
First intracavity saturable absorber - April 1, 1992



U. Keller et al., *Optics Lett.*, vol. 17, 505, 1992

KLM vs. Soliton modelocking





Kerr lens modelocking (KLM)

Fast saturable absorber

D. E. Spence, P. N. Kean, W. Sibbett
Opt. Lett. **16**, 42, 1991

Soliton modelocking

“not so fast” saturable absorber

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

Ultrashort pulse generation with modelocking

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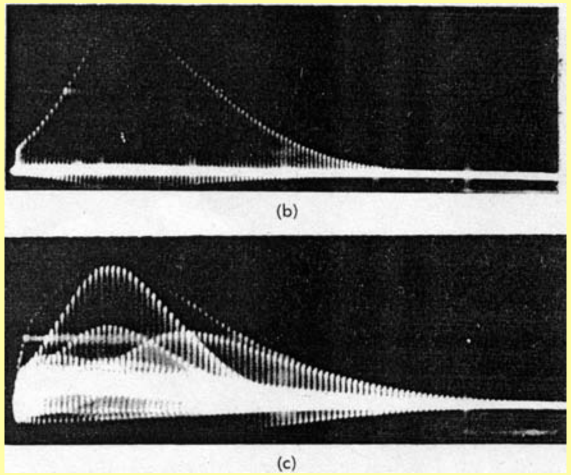


200 ns/div

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

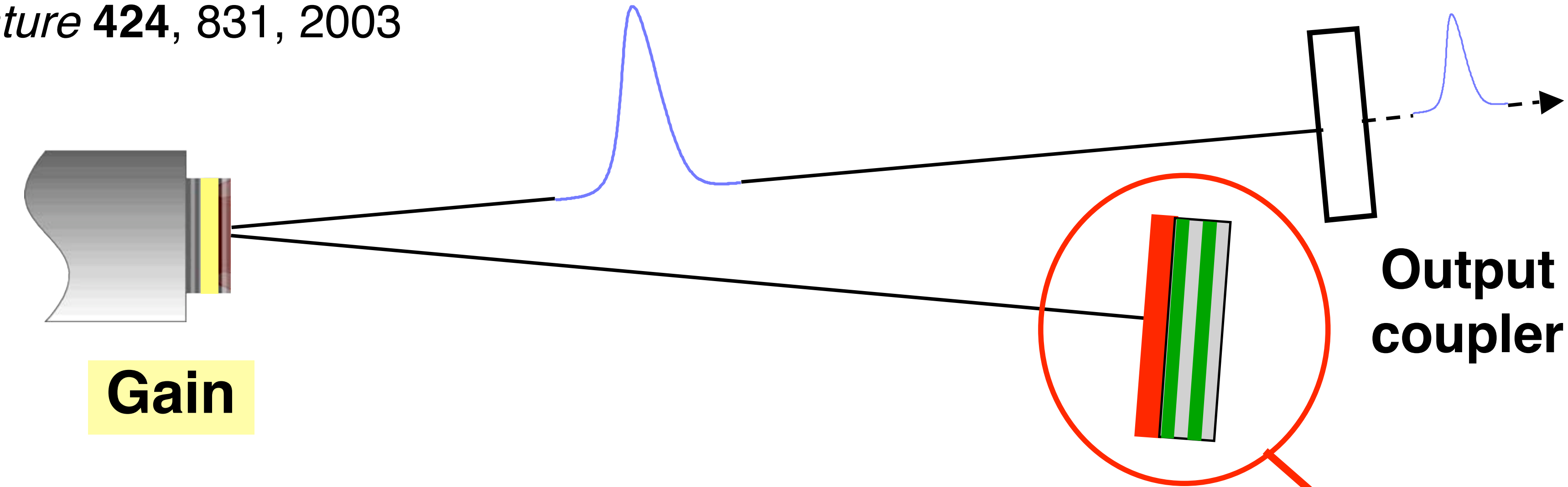
1960 1970 1980 1990 2000
Year

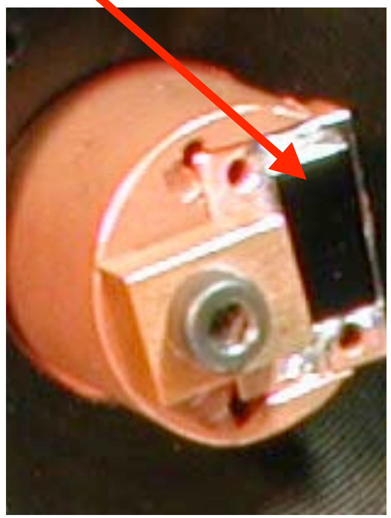
Flashlamp-pumped solid-state lasers

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

SESAM technology – a key technical know-how

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



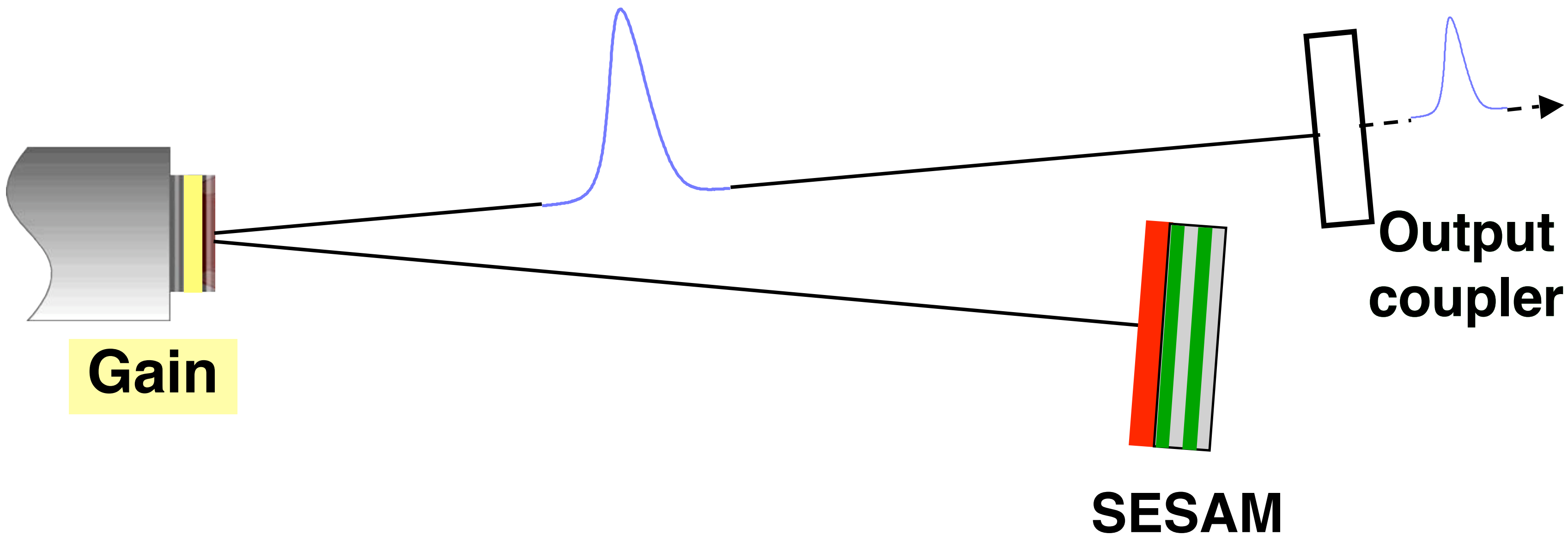


SESAM

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

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

High pulse repetition rate



Short cavity length = high pulse repetition rate

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

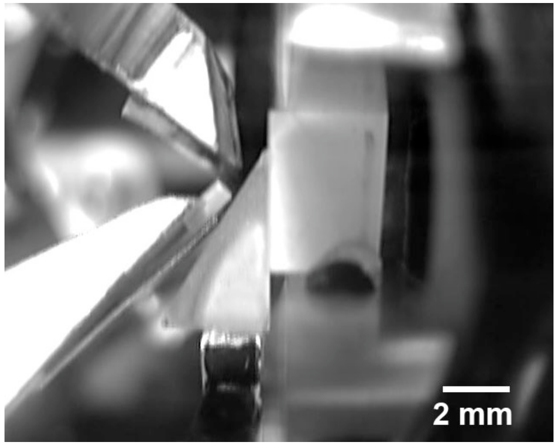
1 GHz: cavity round trip time 1 ns and a cavity length **15 cm**.

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

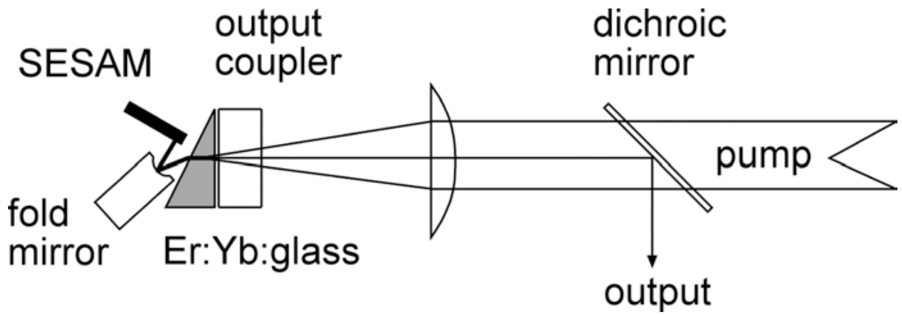
No high speed electronics needed.

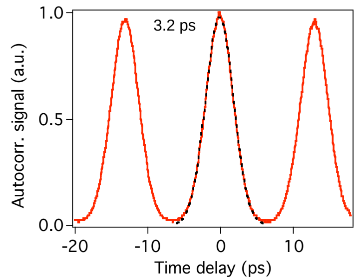
Compact high repetition rate lasers

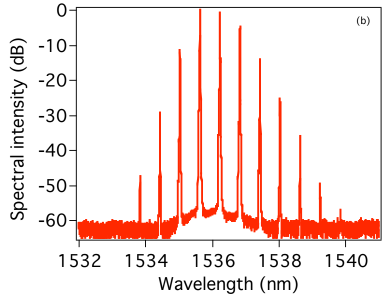
Diode-pumped solid-state lasers:



77-GHz SESAM modelocked Er:Yb:glass laser
Electron. Lett. **43**, 32, 2007

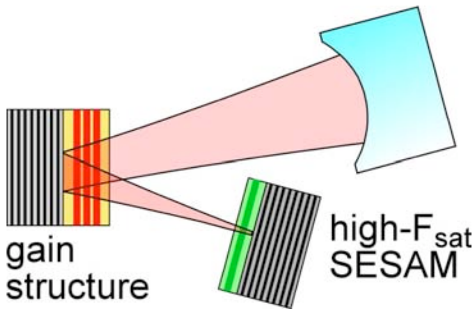






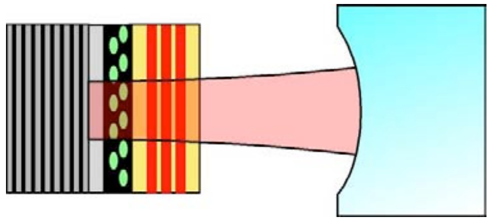
(Optically pumped) semiconductor lasers:

Physics Report **429**, 67-120, 2006



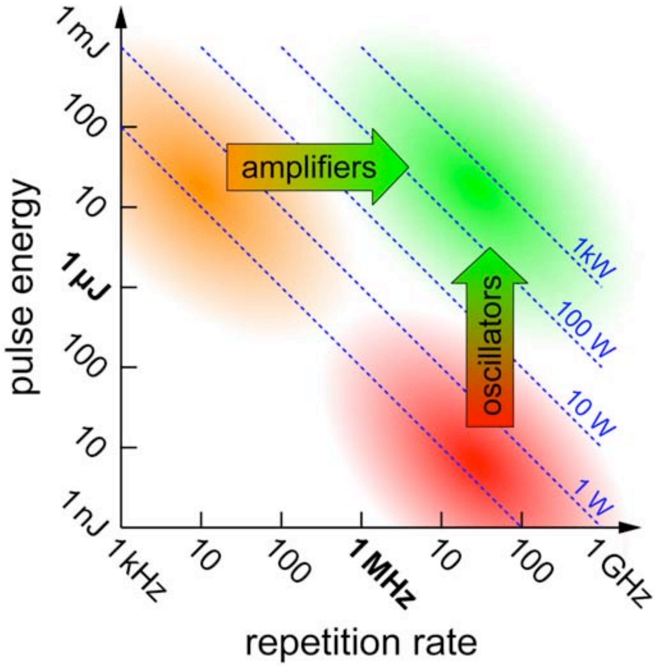
Passively modelocked VECSEL
vertical **e**xternal **c**avity **s**urface **e**mitting **l**aser

Vertical integration of gain and absorber into the same wafer
Appl. Phys. B **88**, 493, 2007

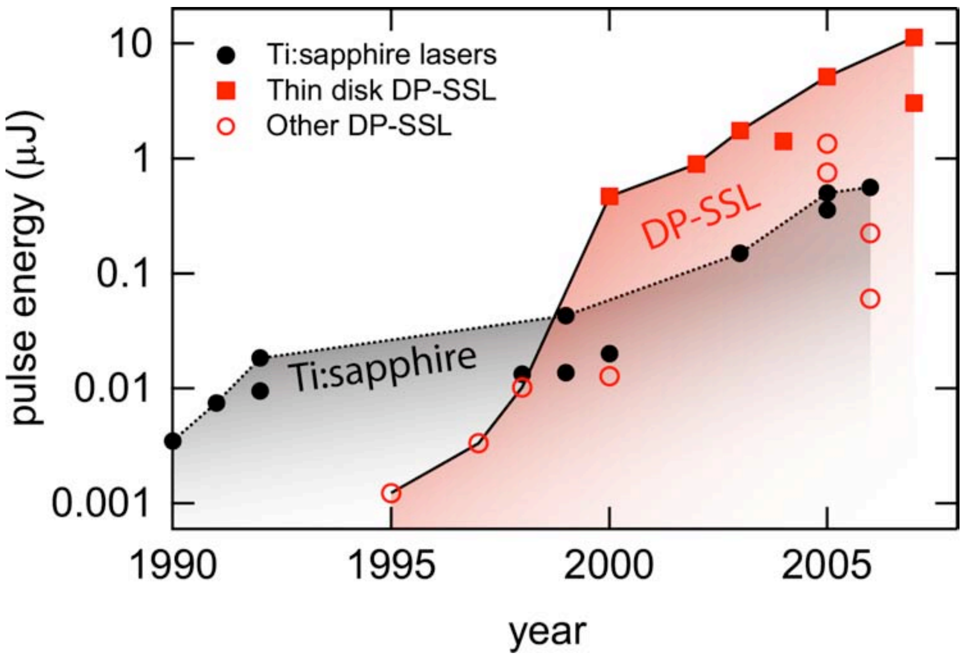


MIXSEL
modelocked **i**ntegrated e**x**ternal-cavity **s**urface **e**mitting **l**aser

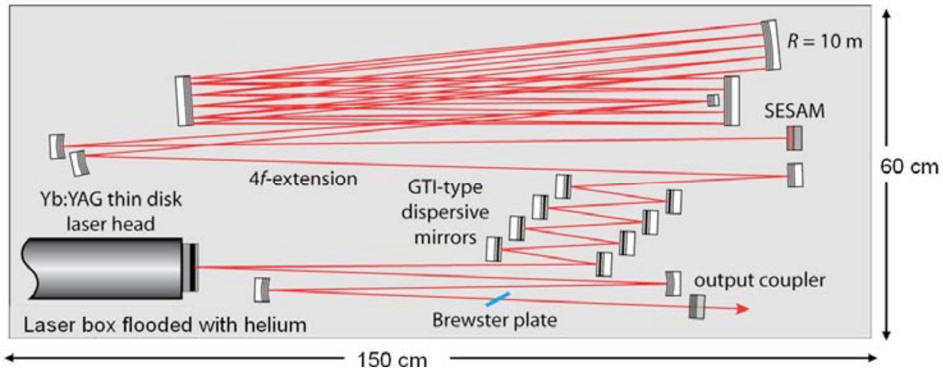
High average power lasers

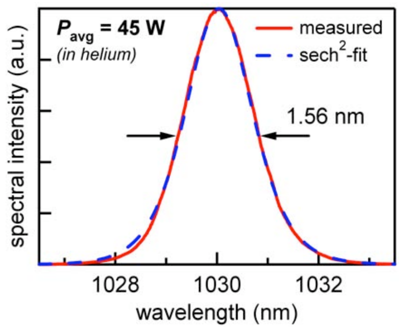


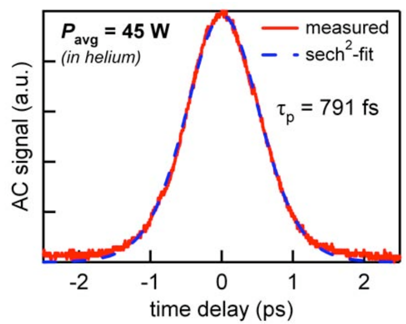
DP-SSL: diode-pumped solid-state lasers



11 µJ pulse energy from a SESAM modelocked Yb:YAG thin disk laser:
>10'000 times improvement in diode-pumped lasers during the last 15 years



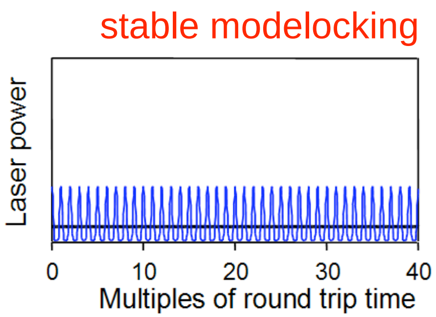


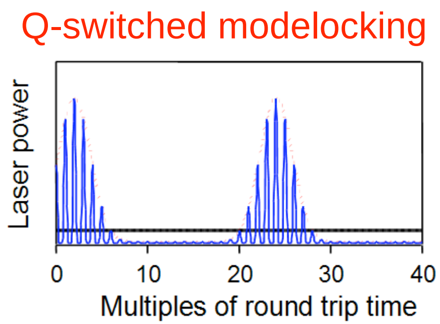


Challenges for high power femtosecond oscillators

- Femtosecond pulse formation at high power levels
  pulse forming element must sustain high intracavity power
  prevent instabilities (e.g. Q-switched modelocking)

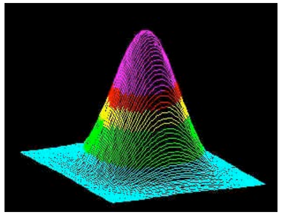
⇨ SESAM for pulse formation





- Laser technology operating at >100 W with Gaussian transverse beam profile (TEM_{00})
  prevent aberrations, provide cooling, …
  Resonator design for stability towards thermal lensing

⇨ Thin disk laser head for high power levels



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)

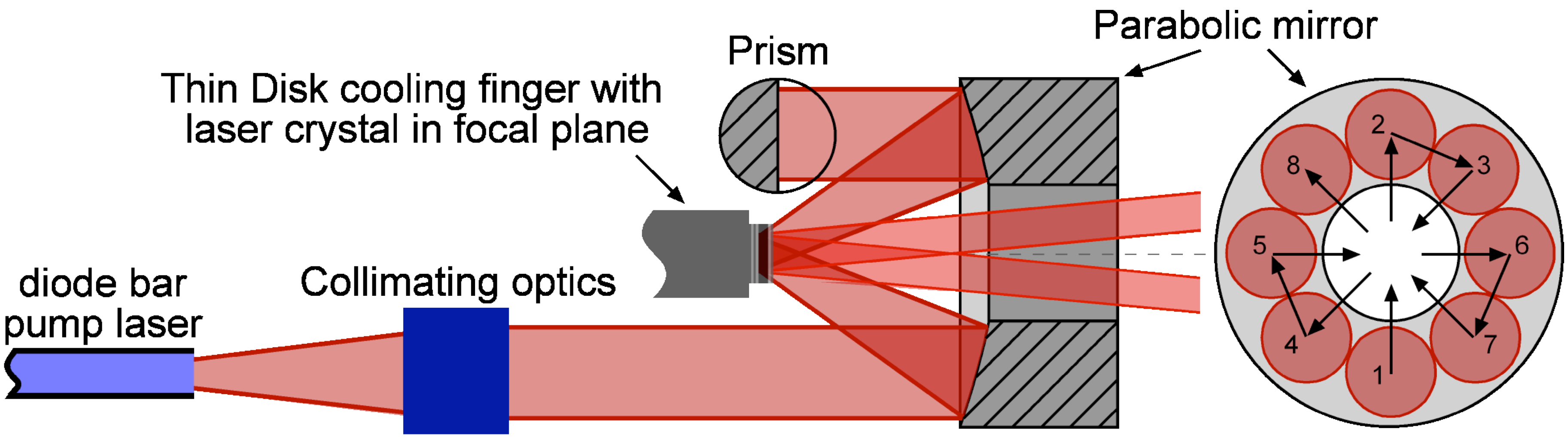
Power scaling

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

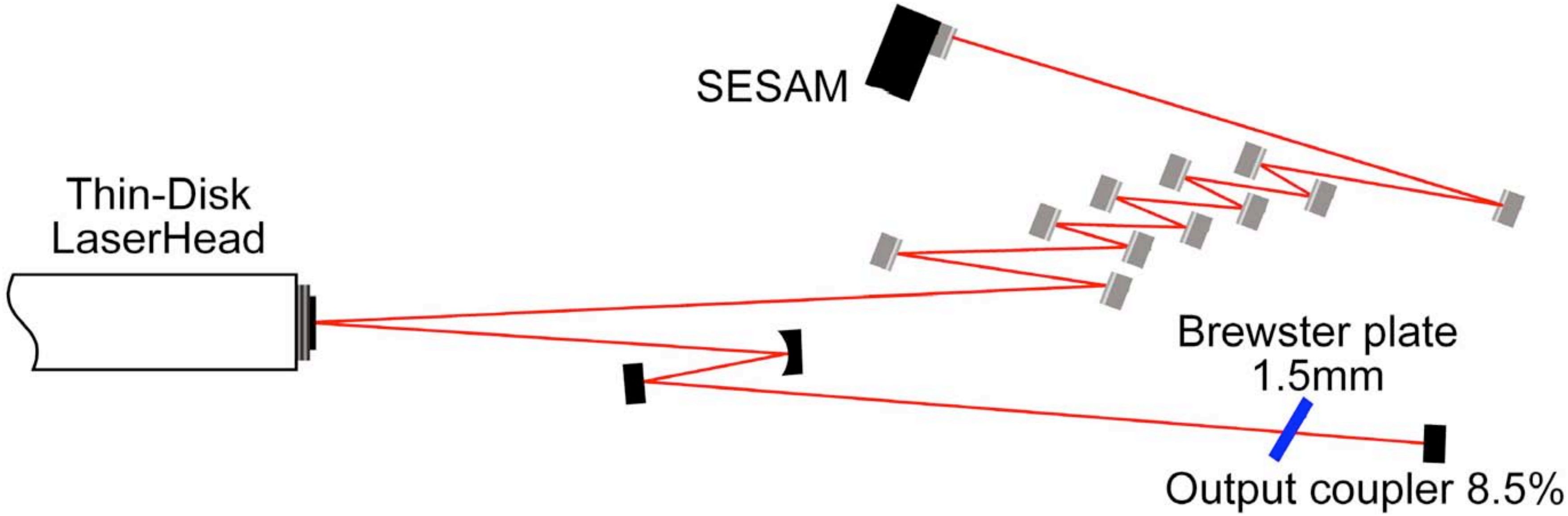
Yb:YAG Thin-Disk Laser Head

A. Giesen et al., *Appl. Phys. B* **58**, 365, 1994
constructed by TRUMPF Laser GmbH+Co. KG (Germany)

- 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



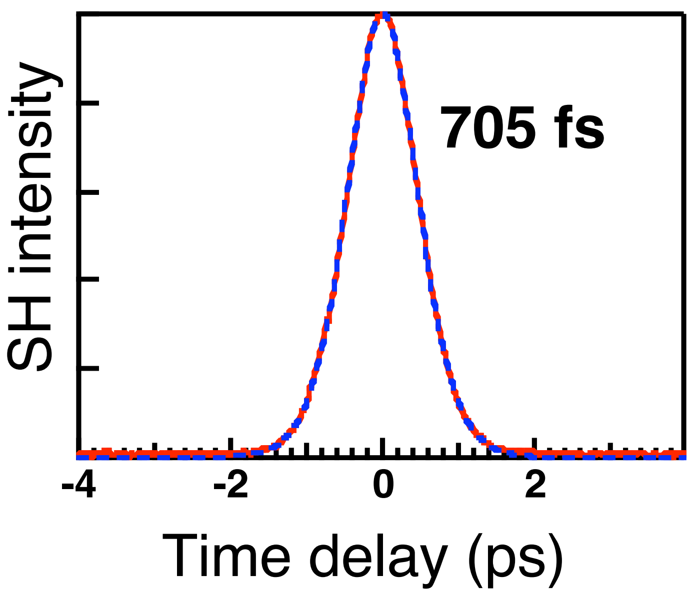
Thin disk laser: 57-MHz setup



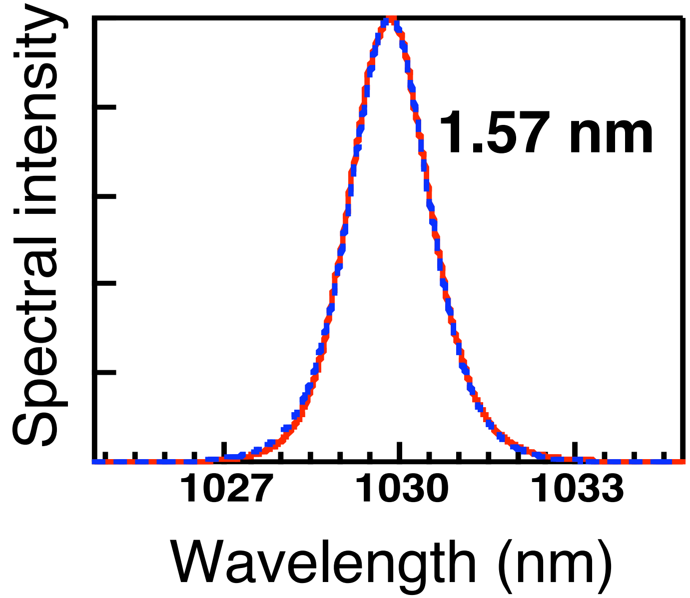
- Thin disk **as folding mirror**
- SESAM and output coupler **as end mirror**
- **Brewster plate for** linear polarization
- **Negative group delay dispersion from** GTI-type dispersive mirrors

80 W from Yb:YAG Laser

Autocorrelation



Optical spectrum

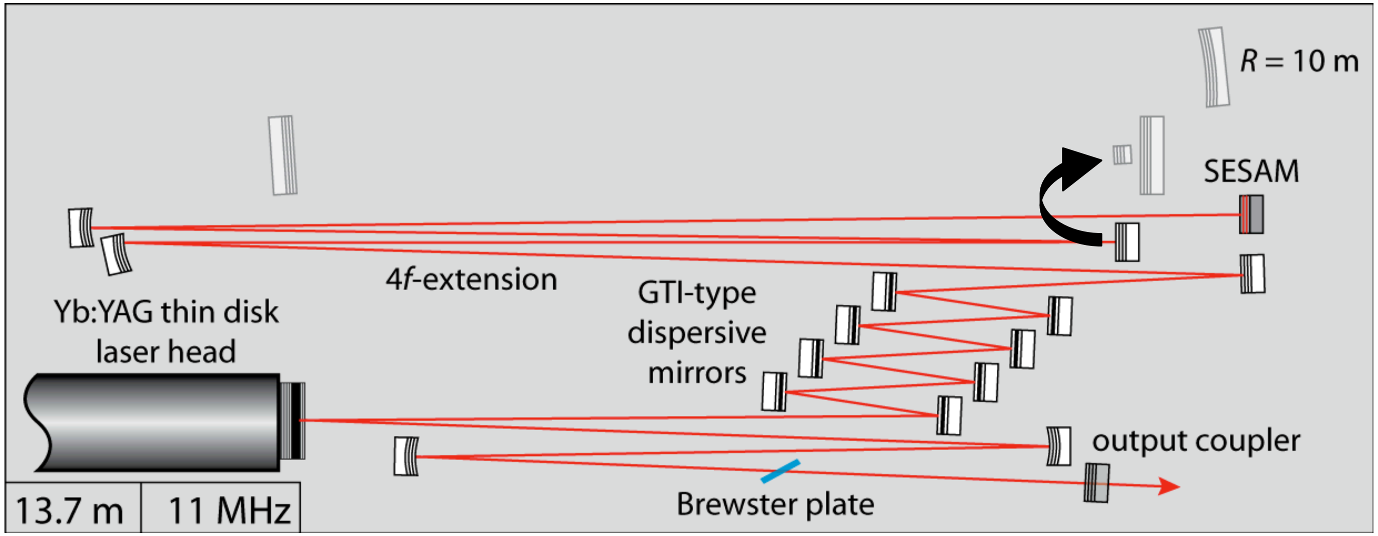


P_{avg} = 80 W
τ_p = 705 fs
f_{rep} = 57 MHz

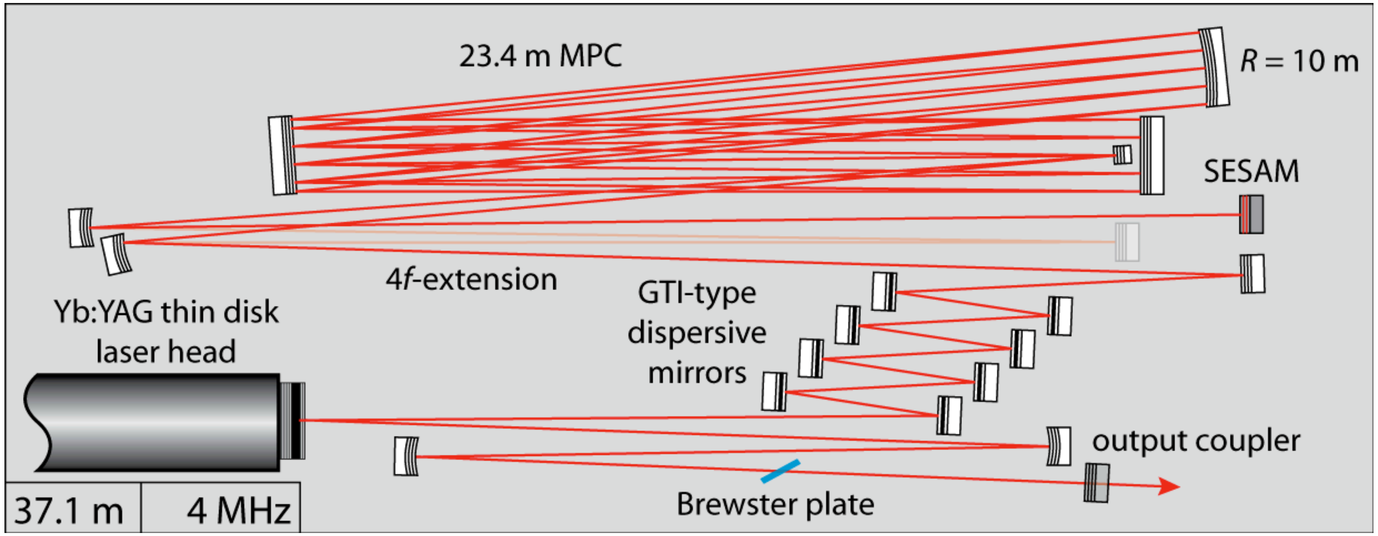
E_p = 1.4 μJ
P_{peak} = 1.75 MW
$\Delta\nu\tau_p$ = 0.32

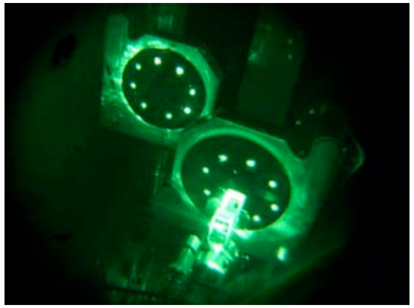
First modelocked (ML) thin-disk, 16 W: *Optics Lett.* **25**, 859, 2000
60 W ML Thin Disk: E. Innerhofer et al., *Optics Lett.* **28**, 367, 2003
80 W ML Thin Disk: F. Brunner et al., *Optics Lett.* **29**, 1921, 2004

Laser setup and results

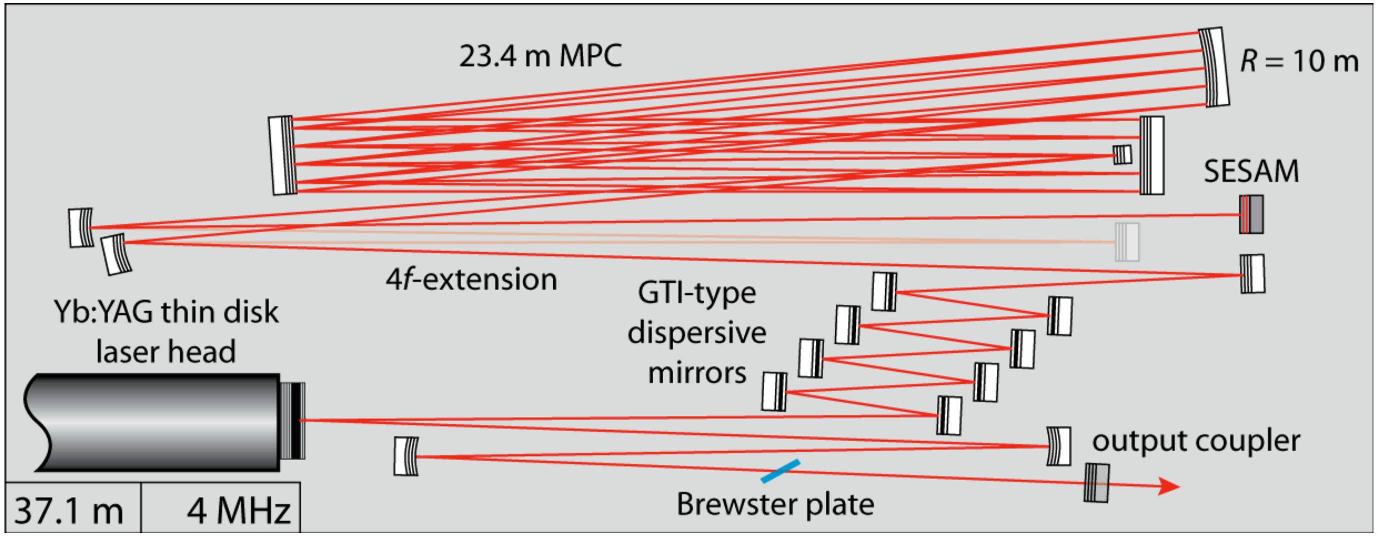


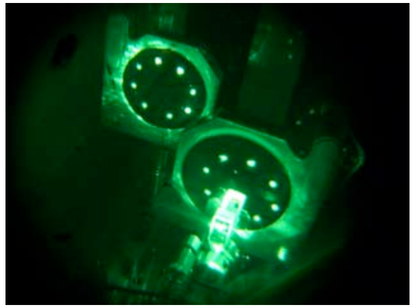
Laser setup and results





Laser setup and results





Yb:YAG laser head

- ≈ 9% Yb-doped YAG
- d_{disk} ≈ 200 µm, w_{pump} ≈ 1.4 mm
- P_{pump} up to 230 W @ 940 nm

(TGSW, Stuttgart, Germany)

SESAM

- F_{sat} ≈ 115 µJ/cm²
- ΔR ≈ 0.5 %

13 dispersive mirrors

- ≈ -550/1000 fs² GDD per bounce
- ≈ -20000 fs² GDD per roundtrip

Brewster plate (SPM + linear pol.)

- 1 mm thick fused silica

Output coupler

- 10% at 1030 nm

Laser setup and results

in air atmosphere

no stable mode locking achieved → instabilities & multiple pulses

in air atmosphere

no stable mode locking achieved → instabilities & multiple pulses

helium flooding

in helium atmosphere

P_{avg} = 45 W

f_{rep} = 4 MHz

→ E_p = 11.3 µJ

pulse energy limited by:

- **strong saturation of the SESAM**
- **air-tightness of the helium box**

in air atmosphere

no stable mode locking achieved → instabilities & multiple pulses

helium flooding

in helium atmosphere

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

→ E_p = 11.3 µJ

pulse energy limited by:

- **strong saturation of the SESAM**
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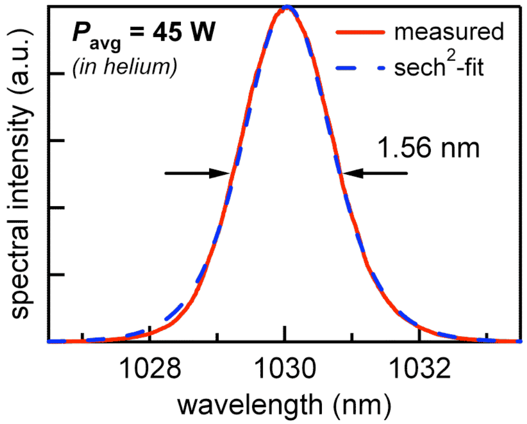

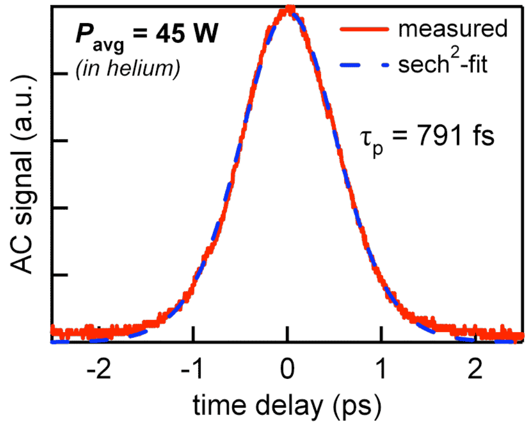

λ = 1030 nm
$\Delta\lambda$ = 1.56 nm

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

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

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J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

Power scaling

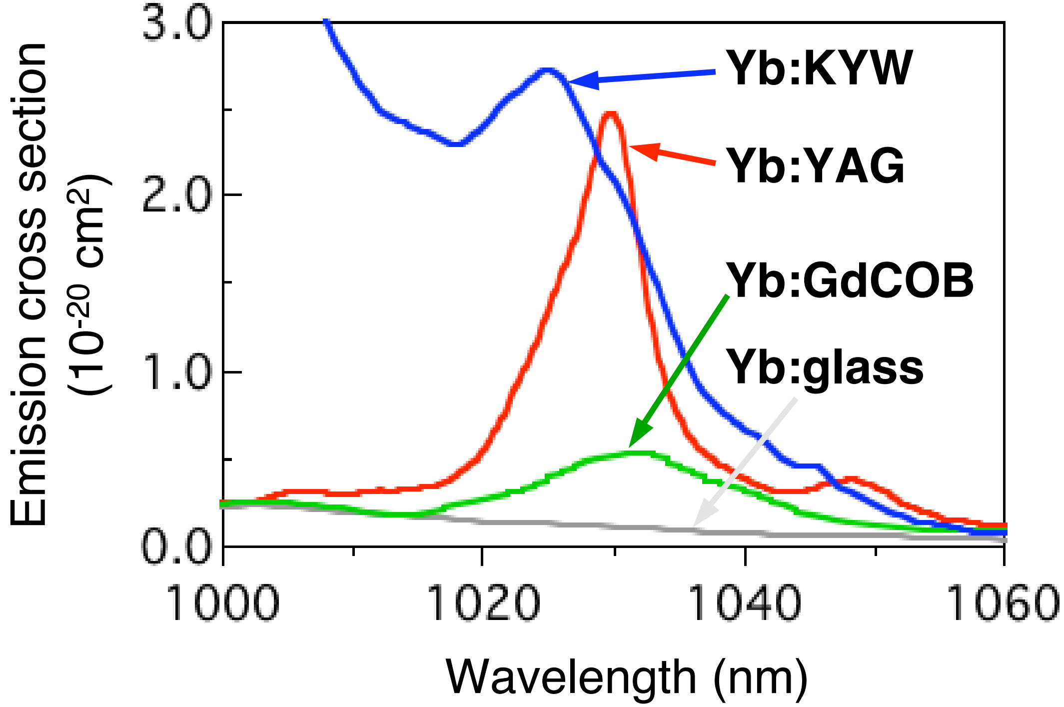
80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

Pulse duration reduced with different laser material Yb:KYW

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

Yb-doped tungstate laser: Yb:KYW {Yb:KY$(WO_4)_2$ }

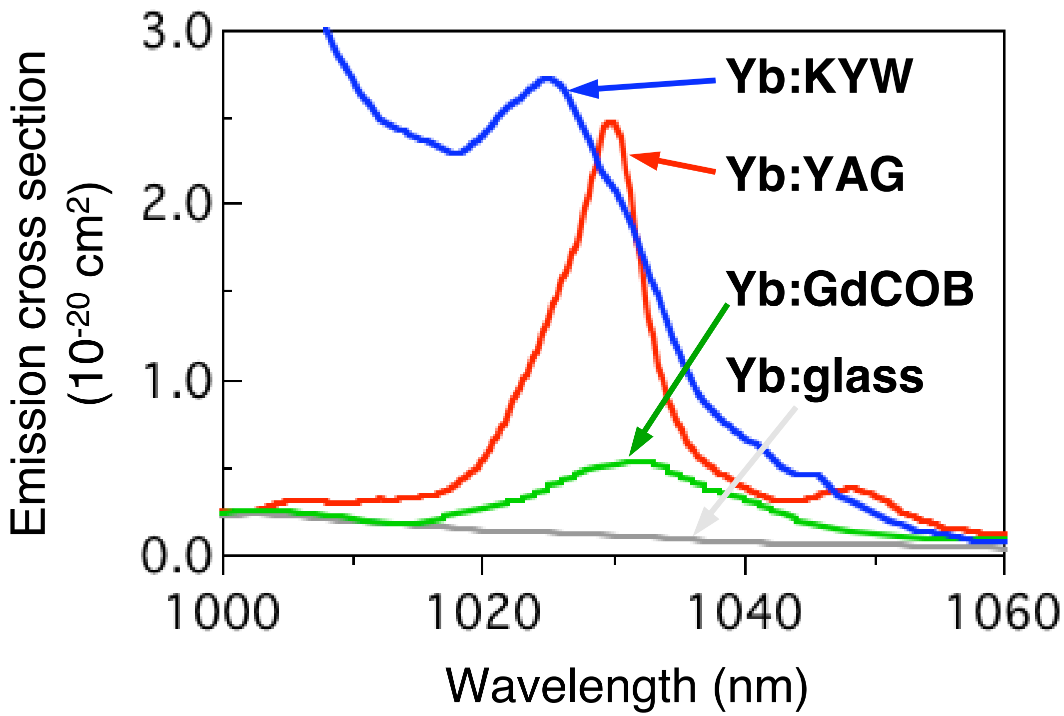
N. V. Kuleshov et al., *Opt. Lett.* **22,** 1317 (1997)



- broad emission spectrum ➡ potential for ≈100-fs pulse
- large emission cross section ➡ lower tendency for QML
- small quantum defect (4%) ➡ reduced heating effects
- good thermal conductivity, κ = 3.3 W/Km ➡ efficient cooling

Yb-doped tungstate laser: Yb:KYW {Yb:KY(WO_4)$_2$ }

N. V. Kuleshov et al., *Opt. Lett.* **22,** 1317 (1997)



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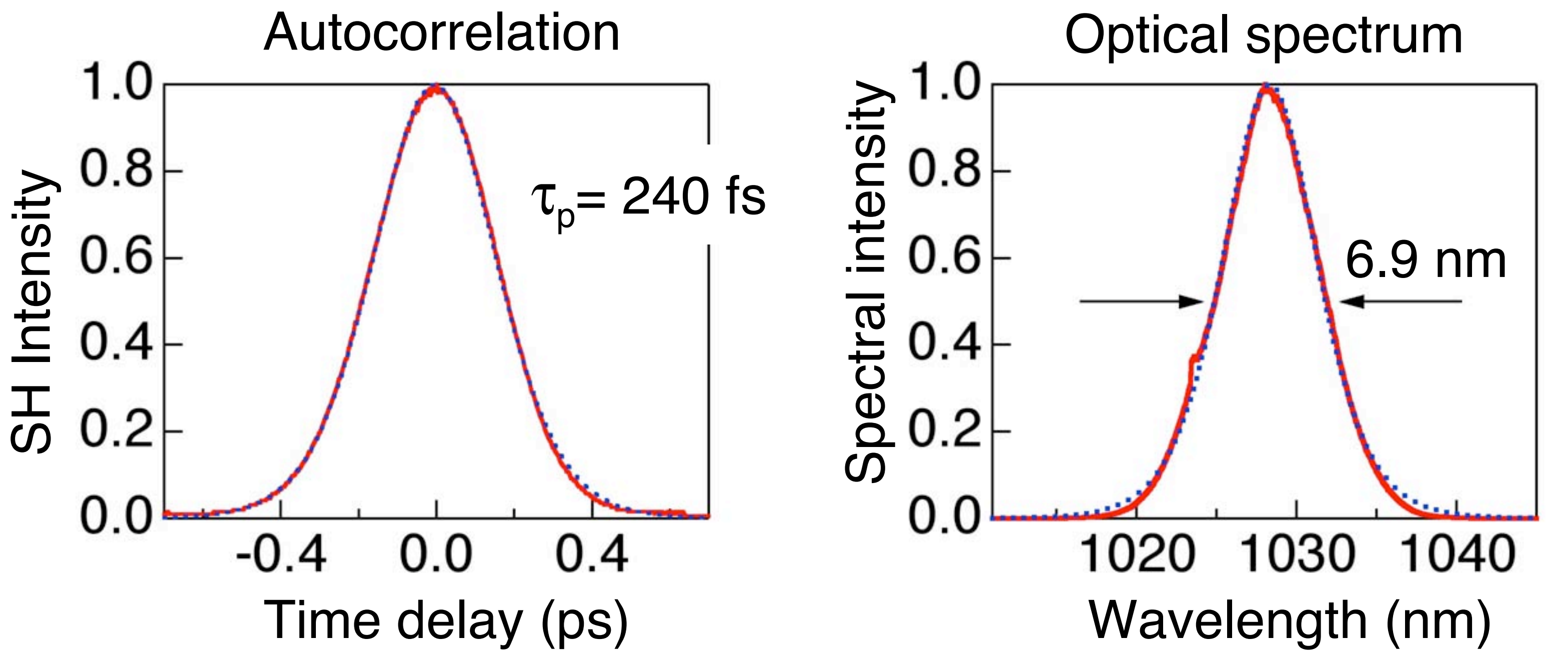
- large emission cross section ➡ lower tendency for QML
- small quantum defect (4%) ➡ reduced heating effects
- good thermal conductivity, κ = 3.3 W/Km ➡ efficient cooling

High power SESAM modelocked Yb:KYW laser

F. Brunner et al., *Opt. Lett.* **27**, 1162 (2002)



P_{avg} = 22 W	E_p = 0.9 μJ
τ_p = 240 fs	P_{peak} = 3.3 MW
f_{rep} = 25 MHz	linear polarisation
M^2 = 1.1	P_{pump} = 100 W

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

Pulse duration reduced with different laser material Yb:KYW

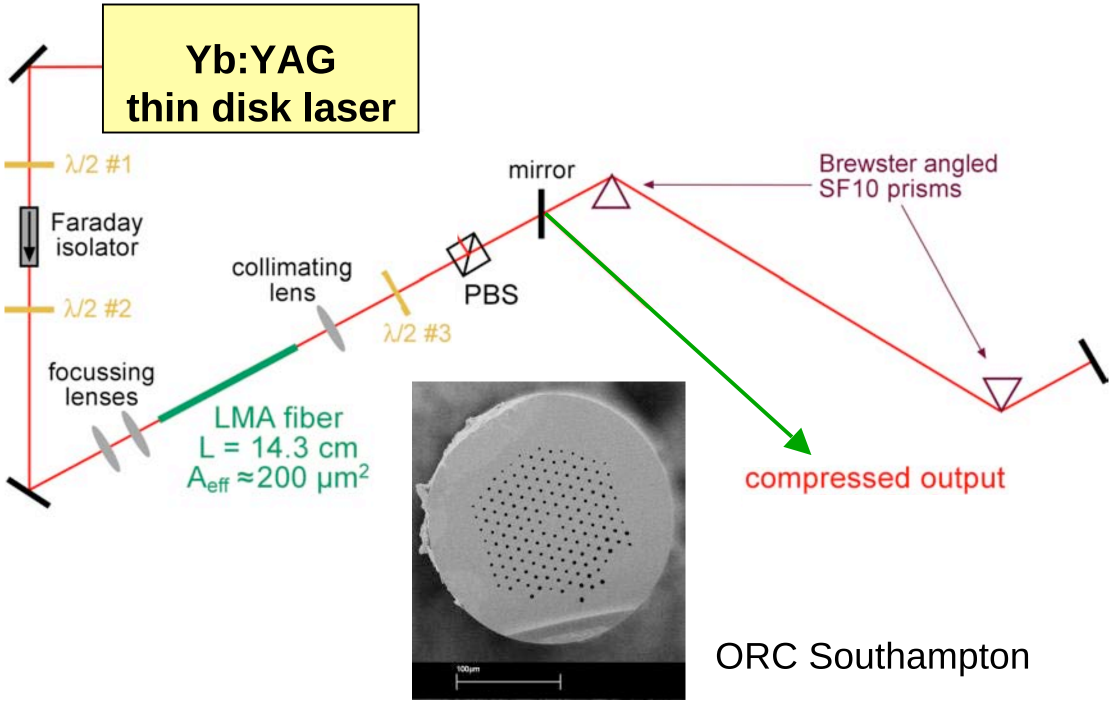
80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

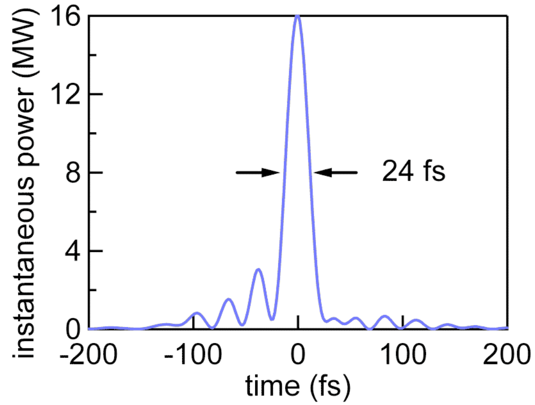
22 W, 240 fs, 3.3 MW
F. Brunner et al.,
Opt. Lett. **27**, 1162 (2002)

even shorter pulse duration?

No laser material

Fiber compression system

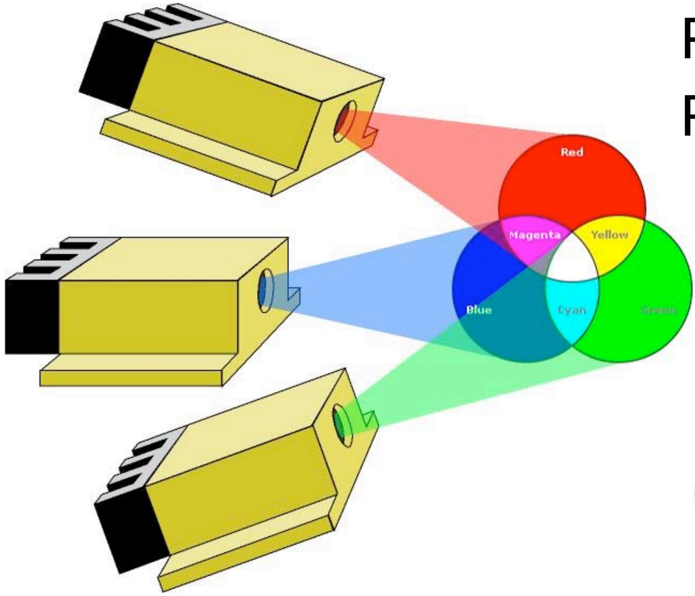




Incident on fiber		**After compression**
P_{peak} = **1.2 MW**	➡	P_{peak} = **16 MW**
τ_p = 760 fs		τ_p = 24 fs
E_{p_inc} = **1 μJ**		E_{p_inc} = **0.6 μJ**

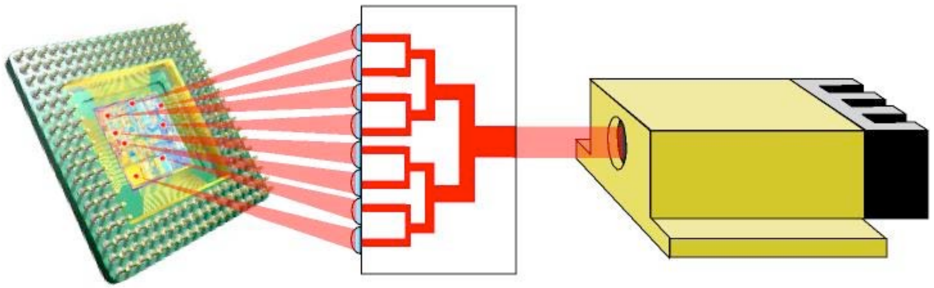
T. Südmeyer et al, Optics Lett. ***28****, 1951 (2003), E. Innerhofer, TuA3, ASSP 2004*

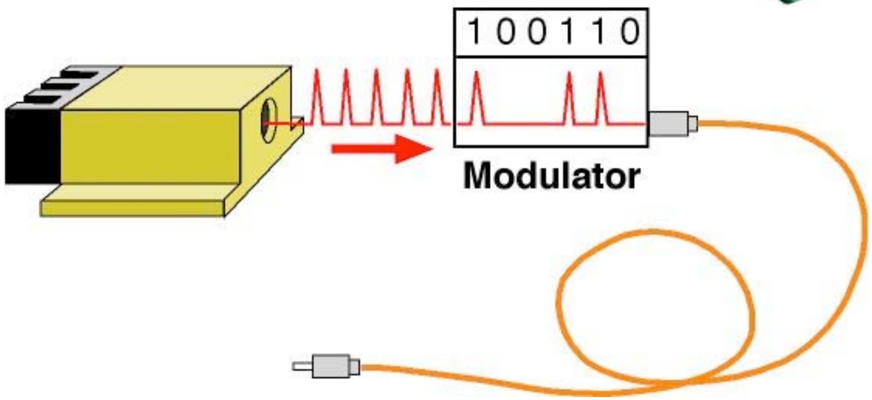
Applications of Multi-GHz Picosecond Laser Sources



Frequency doubling,
RGB Systems

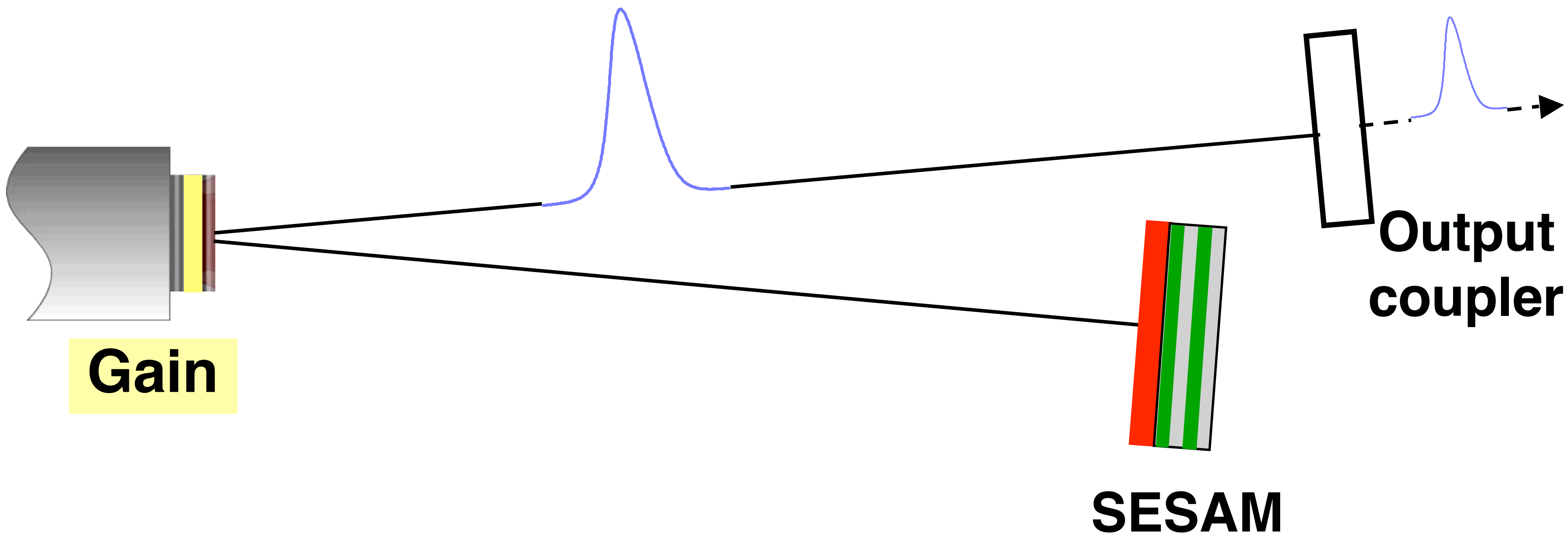
Optical Clocking





Telecommunications

High pulse repetition rate



Short cavity length = high pulse repetition rate

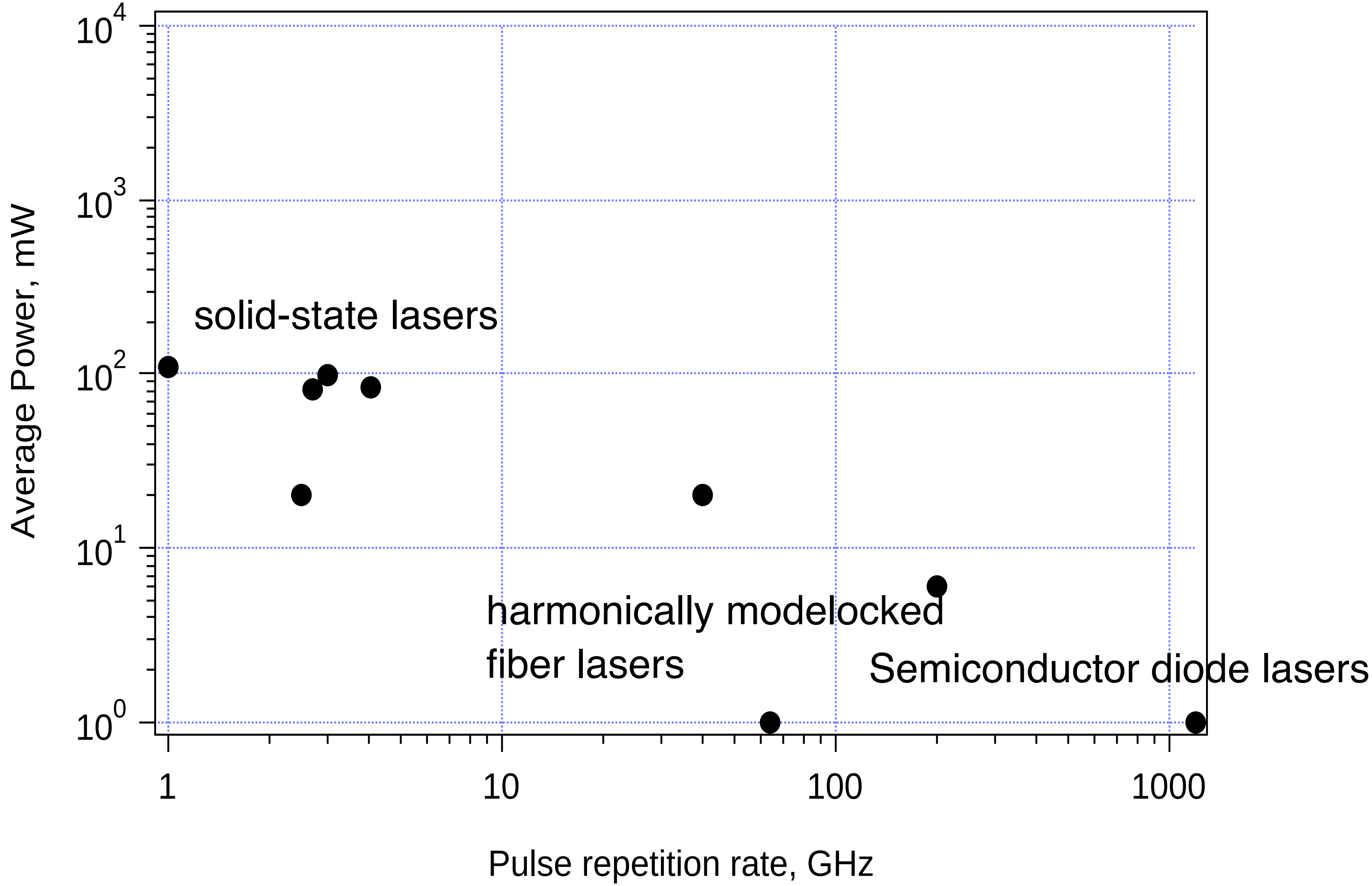
Pulse repetition rate is given by the cavity round trip time.

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

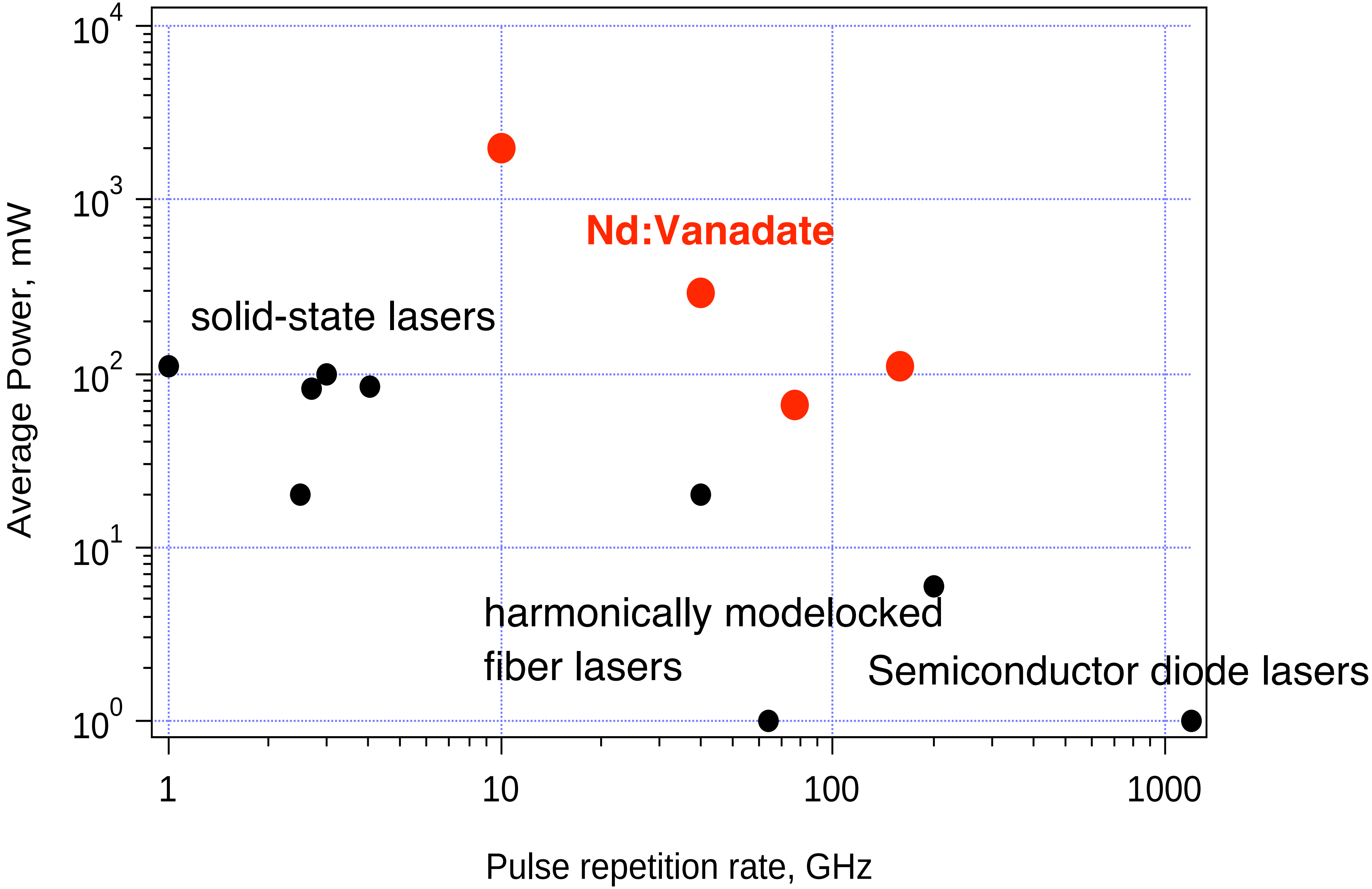
1 THz: cavity round trip time 1 ps and a cavity length **150 µm**.

No high speed electronics needed.

High pulse repetition rate sources

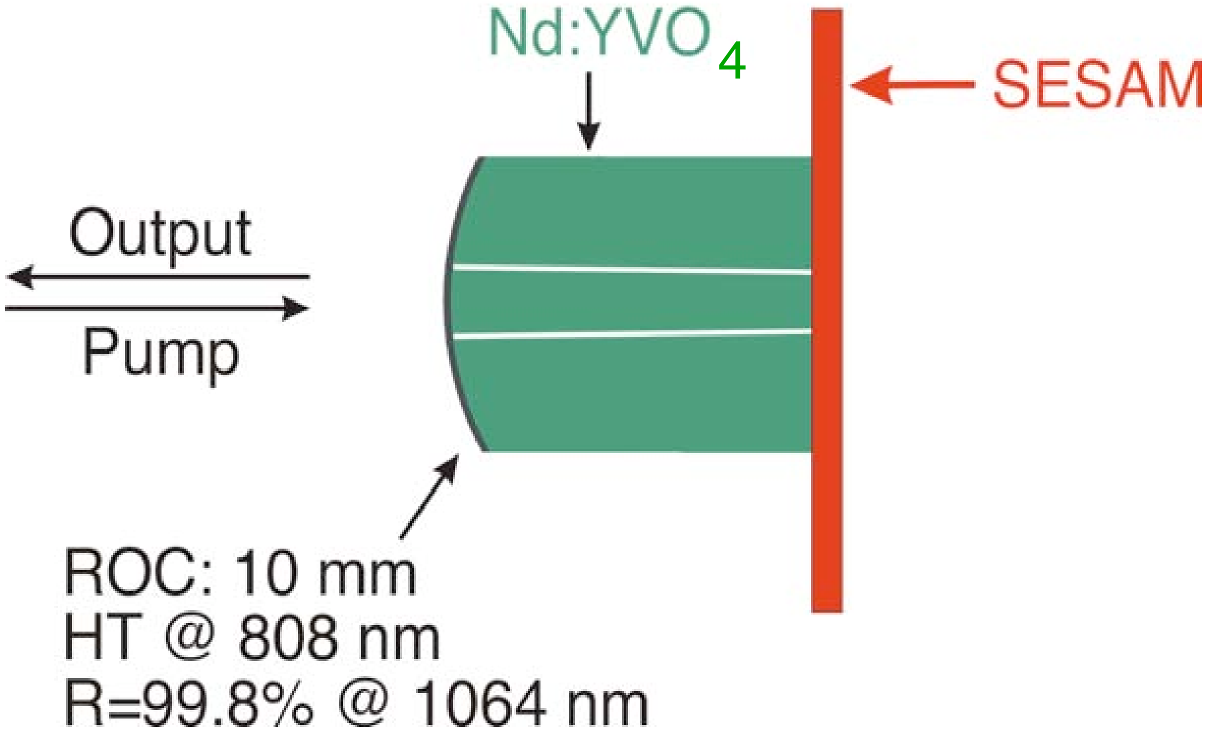


High pulse repetition rate sources



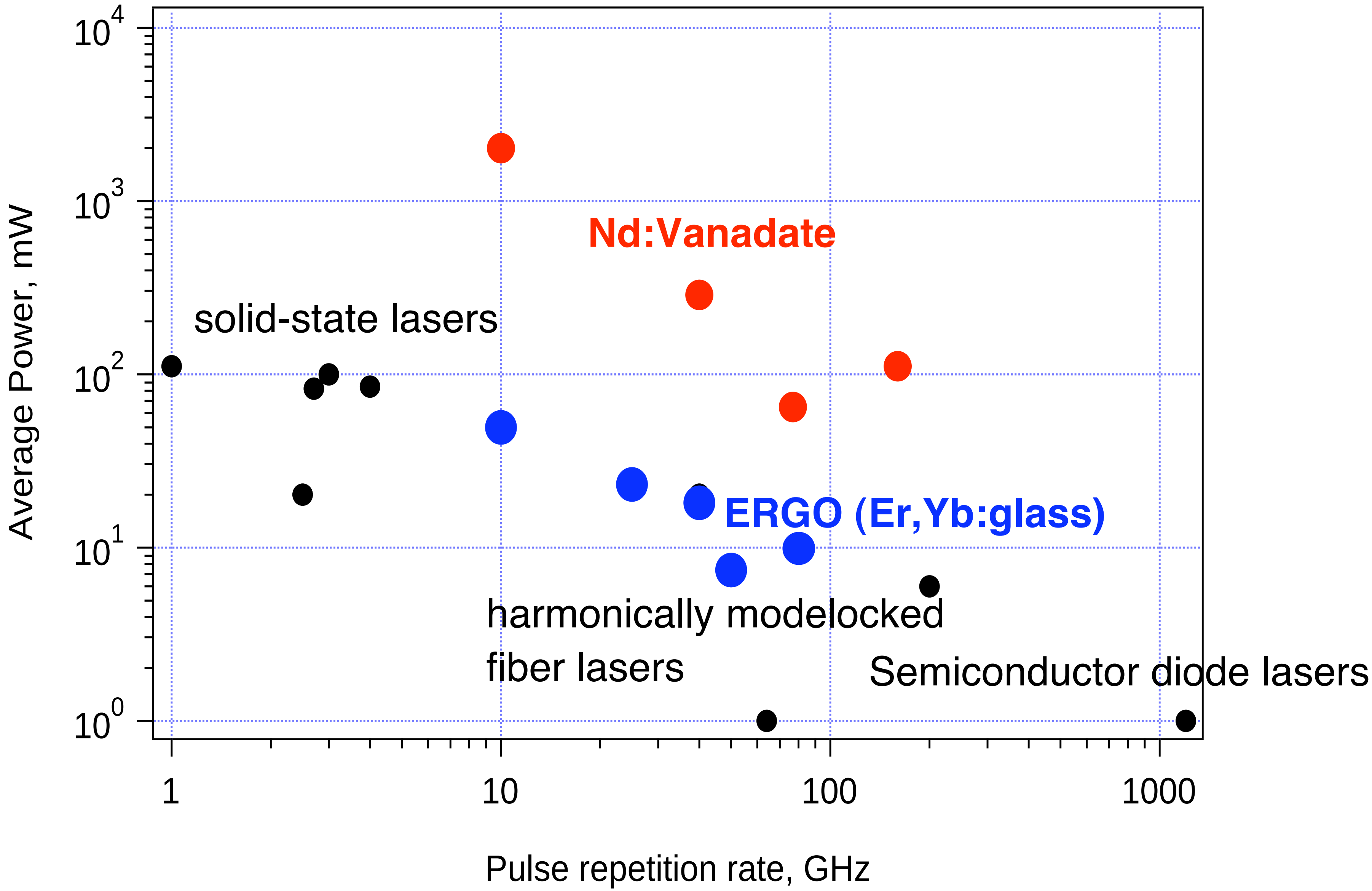
Quasi-Monolithic Cavity Setup

L. Krainer et al., Electron. Lett. ***35****, 1160, 1999 (29 GHz)*
APL ***77****, 2104, 2000 (up to 59 GHz), Electron. Lett.* ***36****, 1846, 2000 (77 GHz)*
IEEE J. Quant. Electron. ***38****, 1331, 2002 (10 to 160 GHz)*

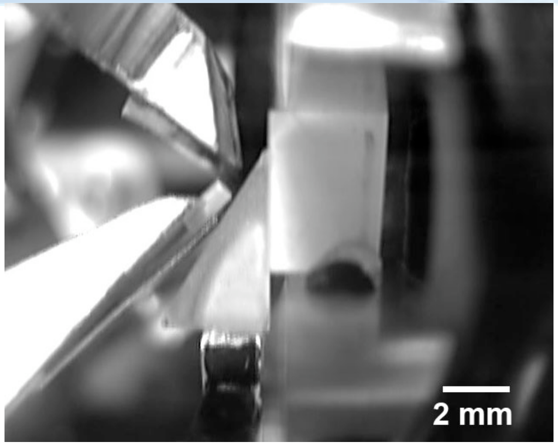


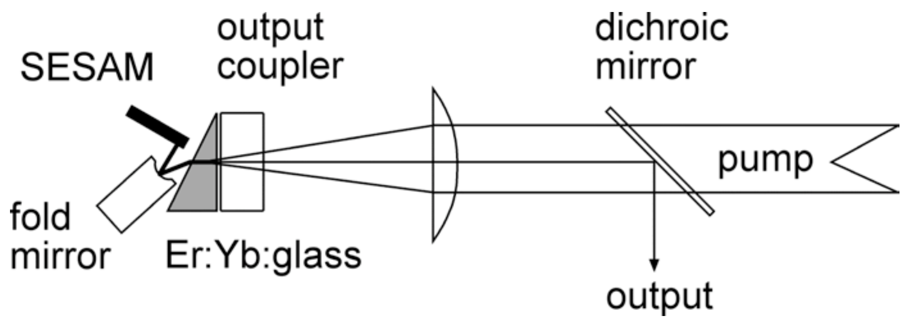
- Crystal lengths: 440 µm - 2.3 mm (FSR ~ 160 - 29 GHz)
- $Nd:YVO_4$ doping: 3 % (90 µm absoption length)

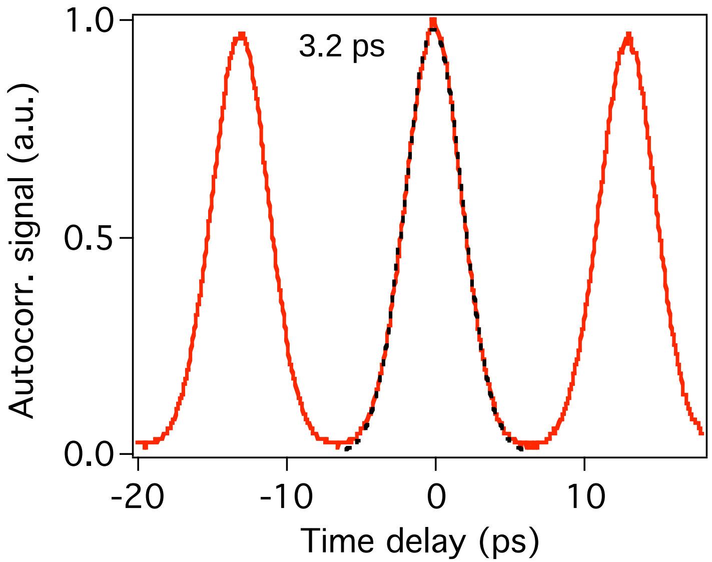
High pulse repetition rate sources

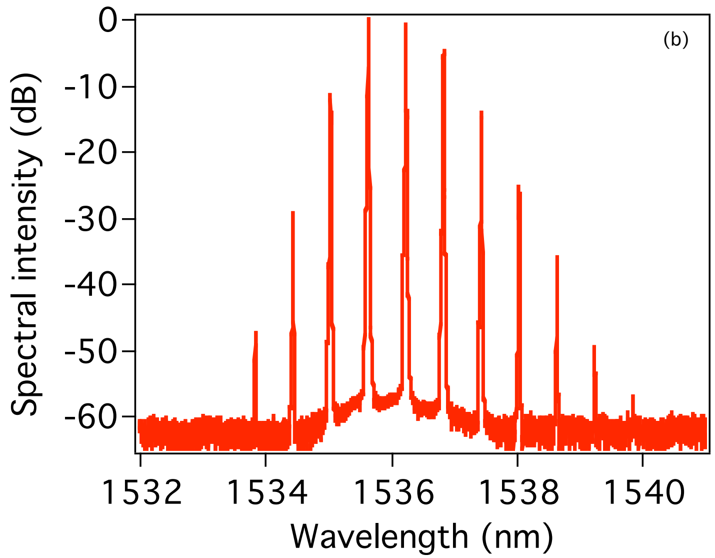


All-optical 77-GHz pulse generation









- 77 GHz at 1538.8 nm (standing wave cavity length 1.9 mm)
- 3.2 ps with average output power of 10 mW, TBP 0.37 (nearly transform limited)

S. C. Zeller et al, *Electron. Lett.*, vol. 43, pp. 32, 2007

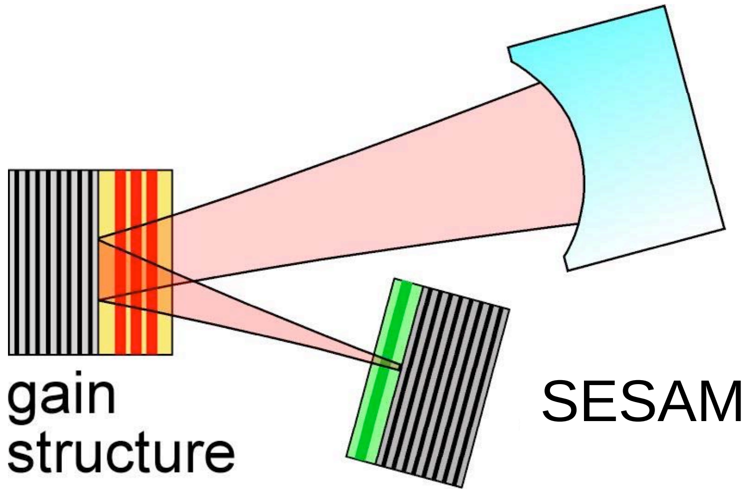
Motivation for semiconductor lasers: Wafer scale integration

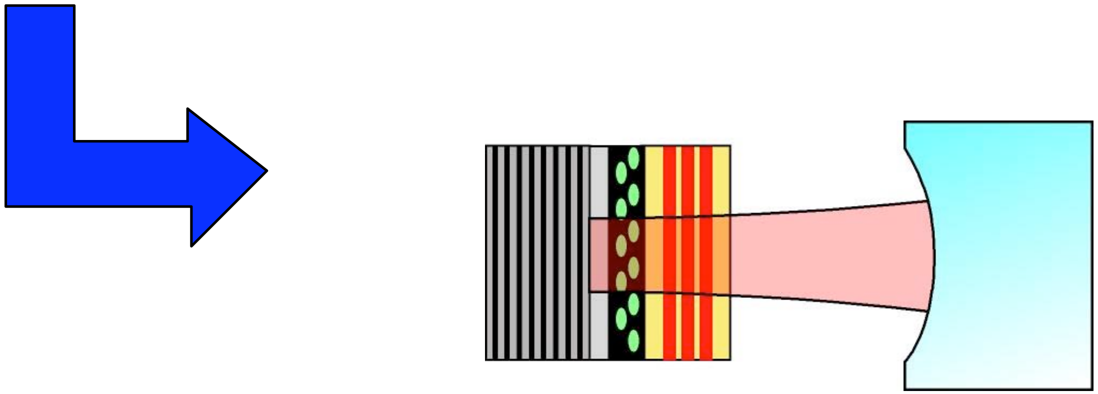
D. Lorenser et al., *Appl. Phys. B* **79**, 927, 2004

Passively modelocked VECSEL

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

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

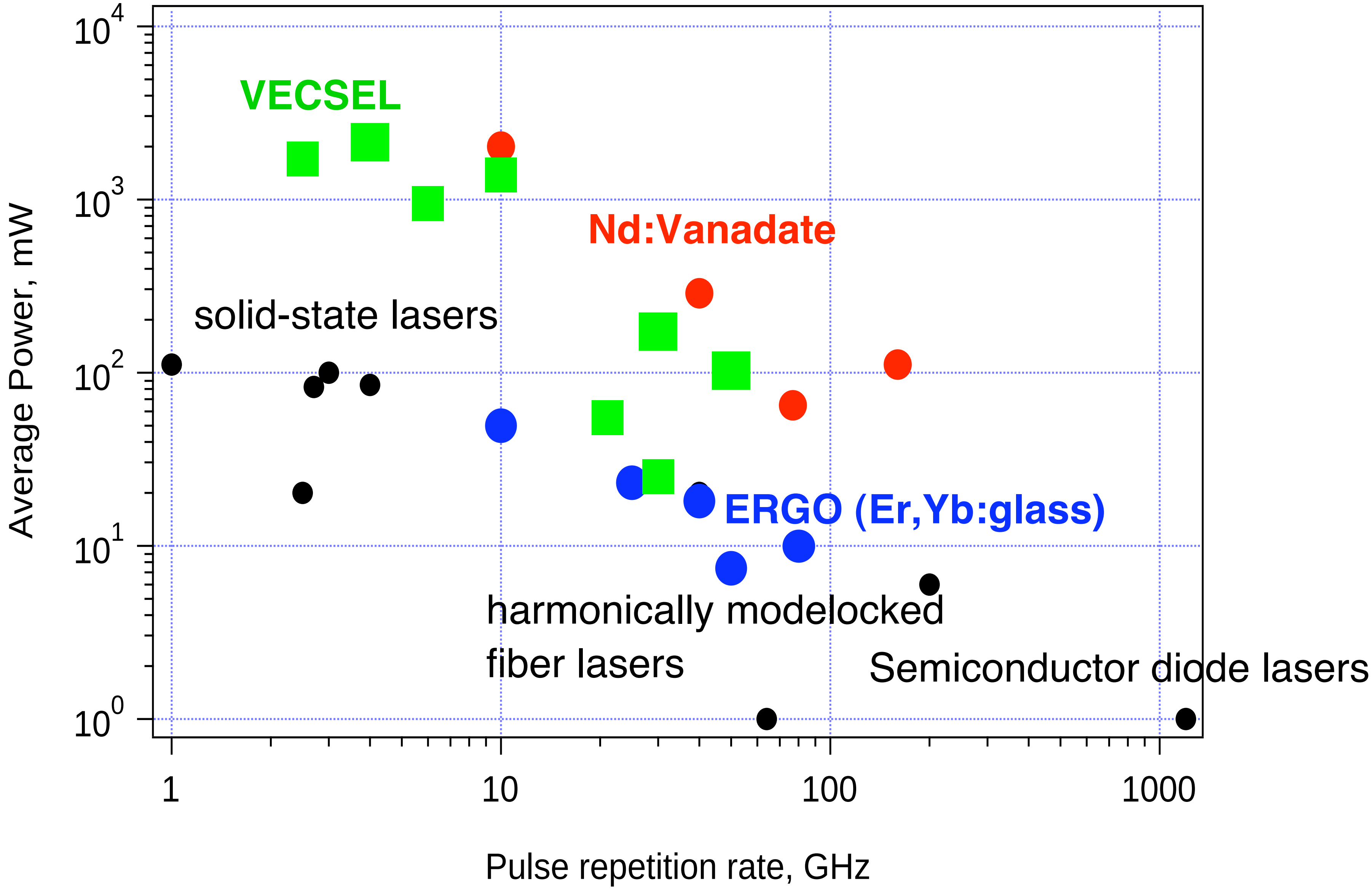




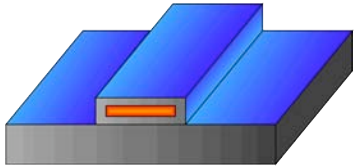
MIXSEL

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

High pulse repetition rate sources

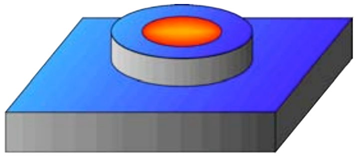


How to Achieve High Powers



Edge-emitting lasers

- Stripe width is limited by beam quality requirements for mode locking
- Nonlinearity and facet damage limit the peak powers



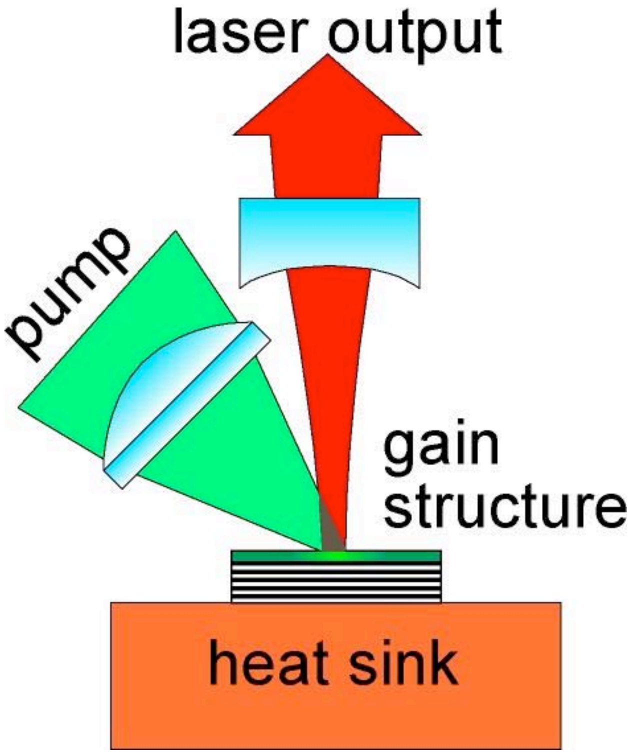
Surface-emitting lasers

- Electrical pumping: ring electrode limits size
- Optical pumping:
  large area with homogeneous inversion
- External cavity needed
  (repetition rate 1 -100 GHz)

Optically pumped Vertical-External-Cavity Surface-Emitting Laser (VECSEL)

OP-VECSEL = **O**ptically **P**umped **V**ertical-**E**xternal-**C**avity **S**urface-**E**mitting Semiconductor **L**aser

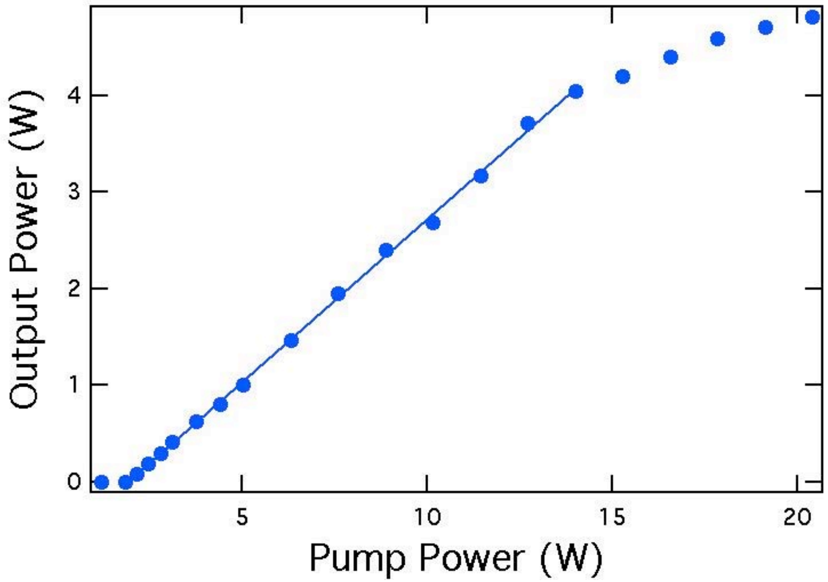
M. Kuznetsov et al., *IEEE Photon. Technol. Lett.* **9**, 1063 (1997)



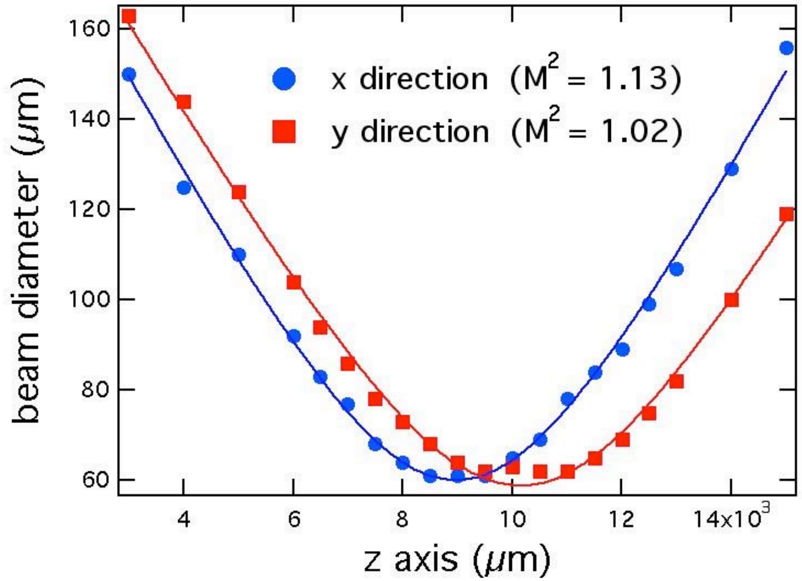
- Semiconductor gain structure with reduced thickness
- Pump: high power diode bar
- External cavity for diffraction-limited output

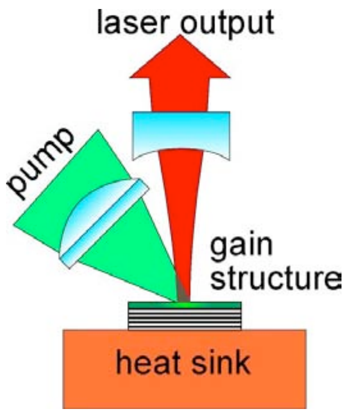
4.4 W cw VECSEL (950 - 960 nm)

Output vs. Input



M² measurement



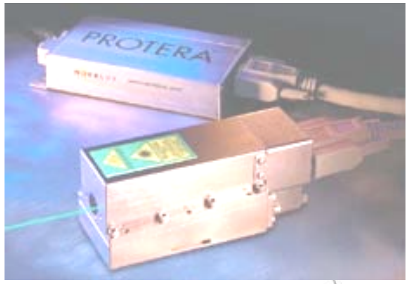


- MOVPE, 7 InGaAs/GaAsP strain-compensated
- Output coupling 1.5%
- Heat sink temperature -5 ºC
- 4.4 W out at 16.6 W pump power, 26% efficiency
- 34% slope efficiency
- M^2 = (1.13,1.02) in (x,y) direction

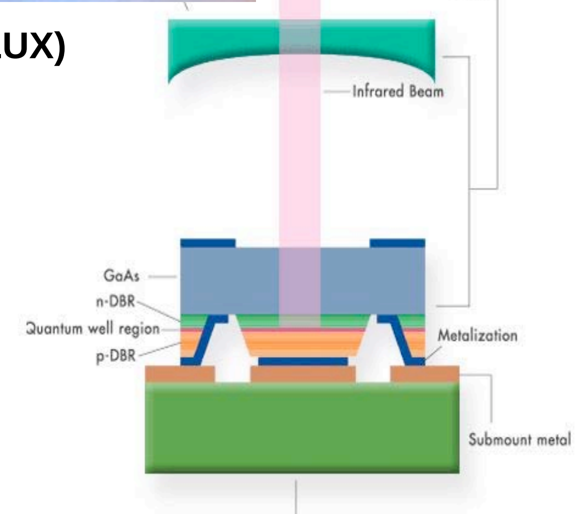
8-W VECSEL with $M^2 < 1.8$ from Osram: S. Ludgen et al., APL 82 (21), 3620 (2003)

Electrical or optical pumping ?

Medium to high powers with good beam quality



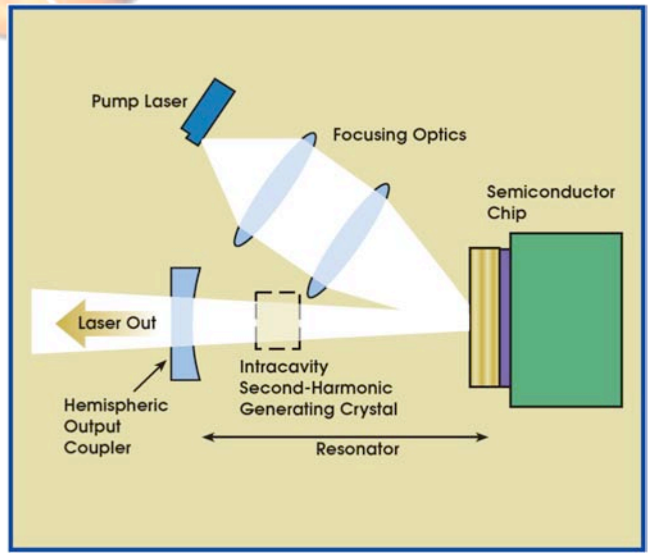
(NOVALUX)



Electrically pumped

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

(COHERENT)



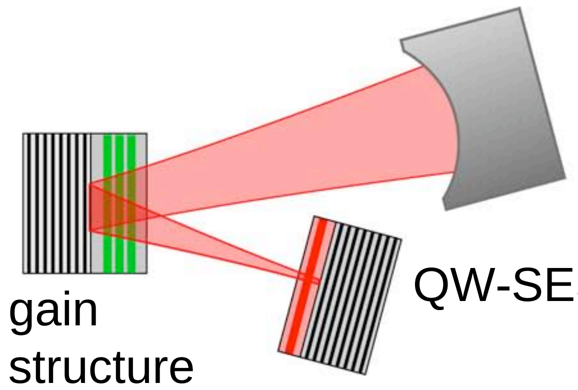
Optically pumped

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

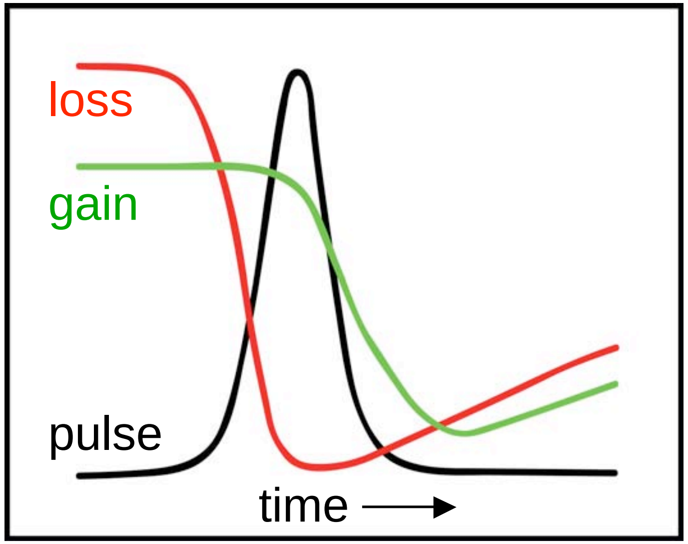
OP-VECSEL milestones

- **First room temperature VECSEL:**
  20 µW average power: *J.V. Sandusky et al., IEEE Photon. Technol. Lett.* 8, 313 (1996)
- **High-power cw operation:**
  0.5 W in TEM_{00} beam: M. Kuznetsov et al., *IEEE Photon. Technol. Lett.* 9, 1063 (1997)
  1.5 W: *W. J. Alford et al., J. Opt. Soc. Am. B* 19, *663 (2002)*
  30 W: J. Chilla et al., *Proc. SPIE* **5332**, 143 (2004)
- **Passive mode locking with SESAM:**
  20 mW: S. Hoogland et al., *IEEE Photon. Technol. Lett.* 12, 1135 (2000)
  200 mW: R. Häring et al., *Electron. Lett.* 37, 766 (2001)
  950 mW: R. Häring et al., *IEEE JQE* 38, 1268 (2002)
  2.1 W, 4.7 ps, 4 GHz, 957 nm: A. Aschwanden et al., *Opt. Lett. 30, 272 (2005)*
  Modelocked VECSEL review: *Physics Reports* **429**, 67, 2006

VECSEL Modelocking



< 20 GHz



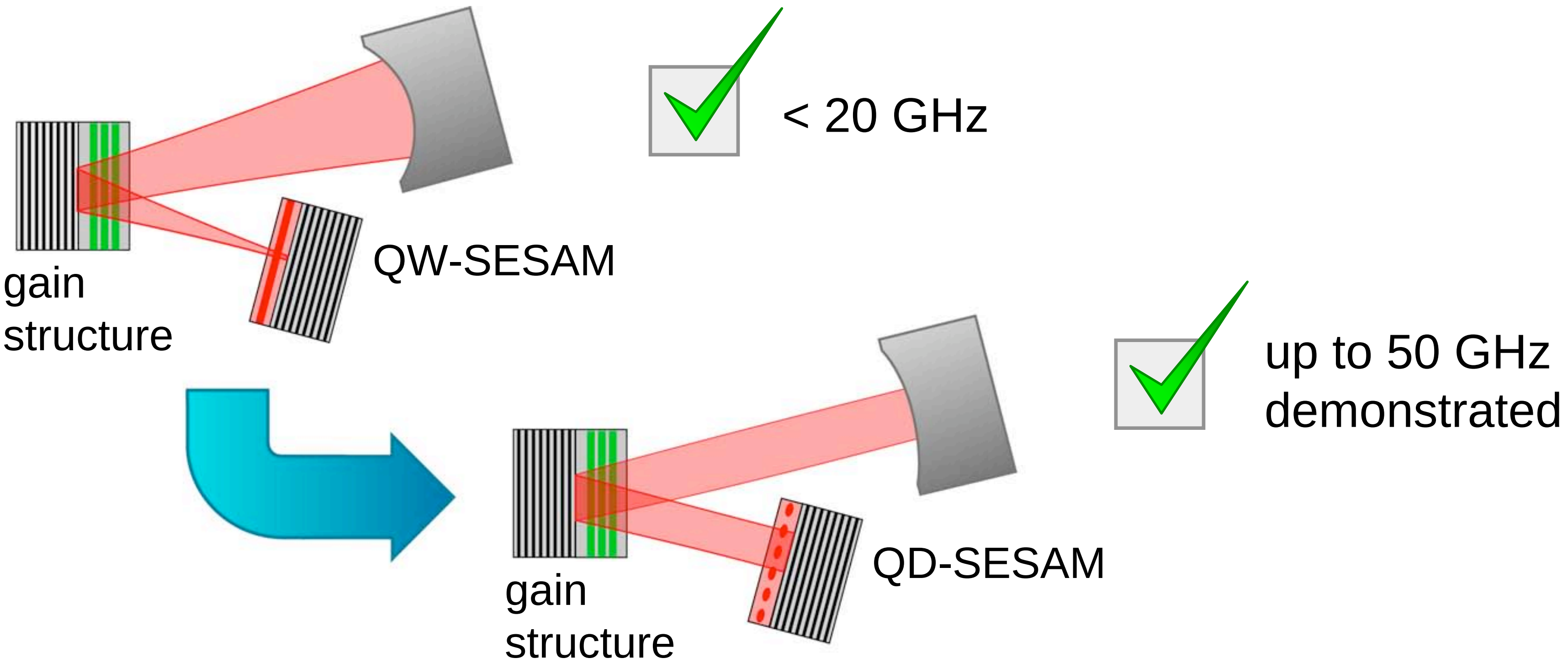
First passively mode-locked VECSEL:

S. Hoogland et al., IEEE Phot. Tech. Lett., vol. 12, pp. 1135-1138, 2000.

Highest output power (2.1 W):

A. Aschwanden et al., Opt. Lett., vol. 30, pp. 272-274, 2005.

VECSEL Modelocking



First passively mode-locked VECSEL:

S. Hoogland et al., IEEE Phot. Tech. Lett., vol. 12, pp. 1135-1138, 2000.

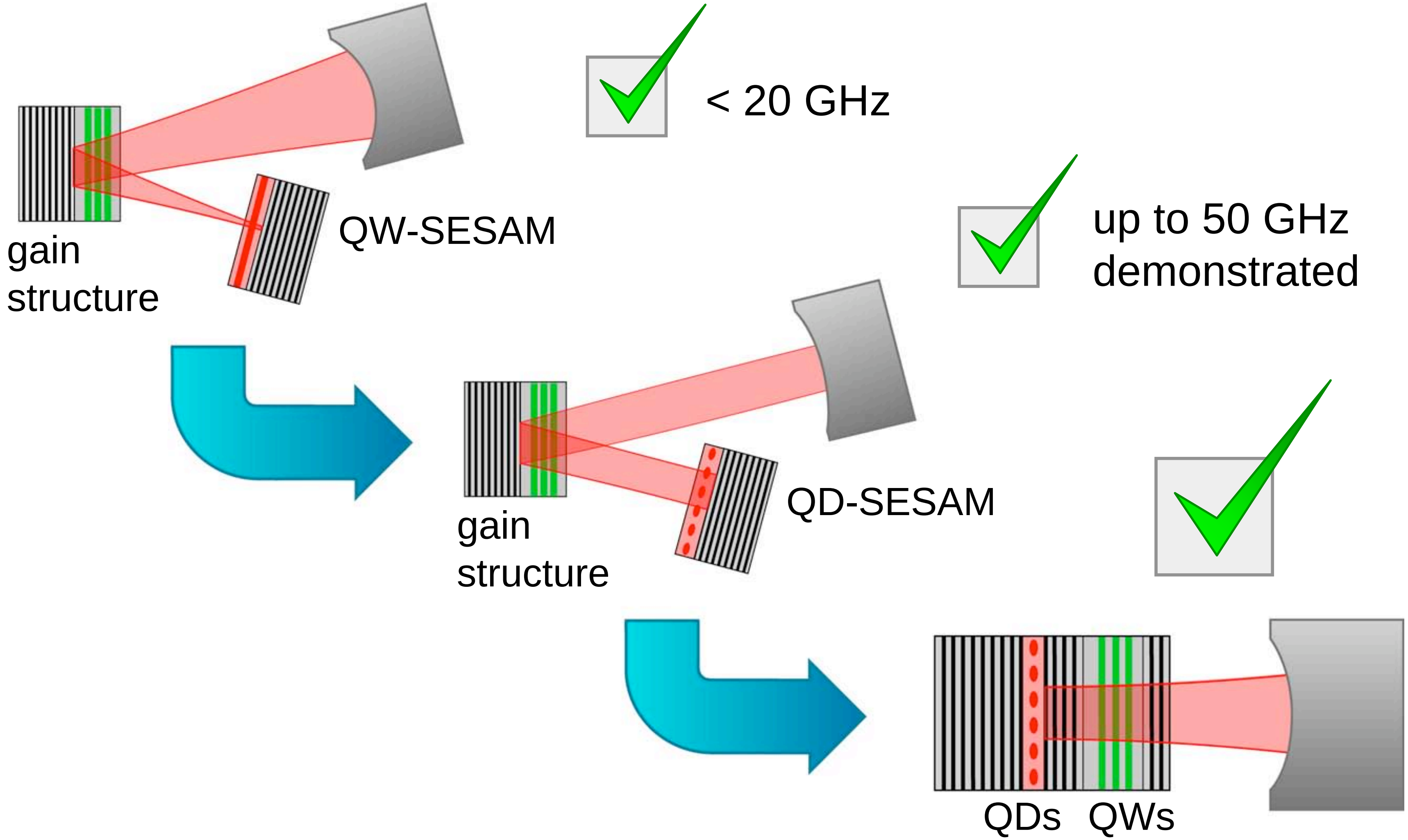
Highest output power (2.1 W):

A. Aschwanden et al., Opt. Lett., vol. 30, pp. 272-274, 2005.

QD-SESAM modelocking (50 GHz):

D. Lorenser et al., IEEE J. Quantum Electron., vol. 42, pp. 838-847, 2006.

From VECSEL to MIXSEL

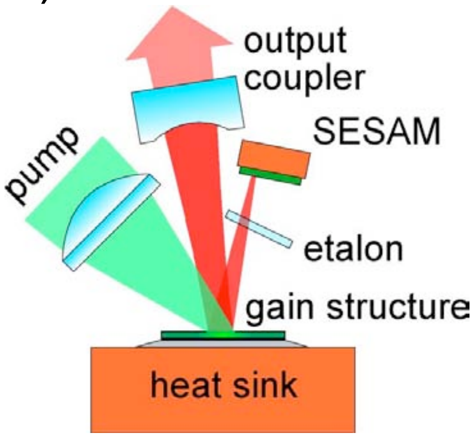


MIXSEL

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

High-power ML VECSELs (up to **2.1 W** at **4 GHz**)

- High peak power (100 W) due to short pulses (few ps)



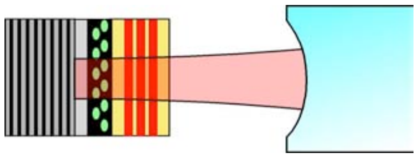
ML VECSELs at 1.3 μm and 1.5 μm

- InGaAsP-based: 3 GHz, 120 mW, 3.2 ps
- All GaInNAs-based: 6 GHz, 57 mW, 18.7 ps

High-repetition-rate ML VECSELs (up to **100 mW** at **50 GHz**)

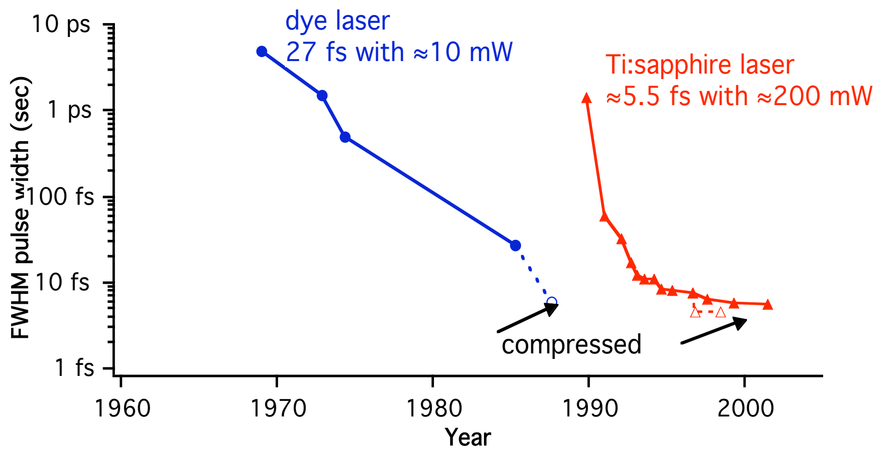
- Much higher average output power directly from oscillator than ML edge-emitting semiconductor lasers
- Demonstration of 1:1 mode locking proves the feasibility of integrating absorber and gain in same structure
- Applications: optical clocking of integrated circuits

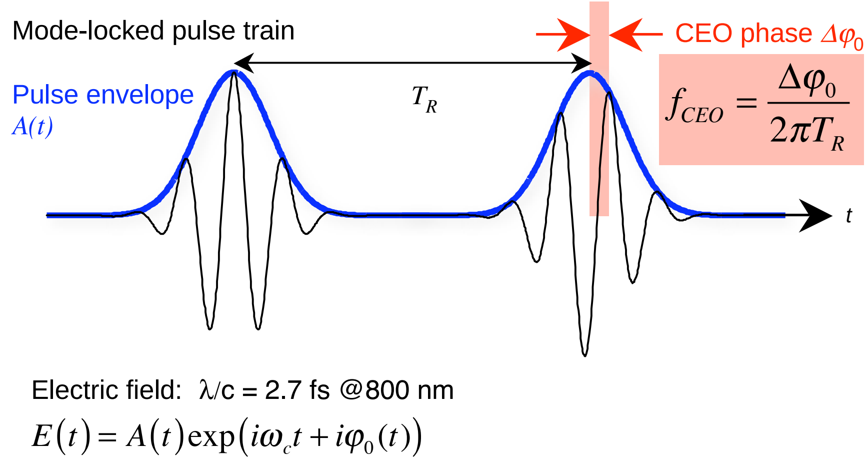
Future work



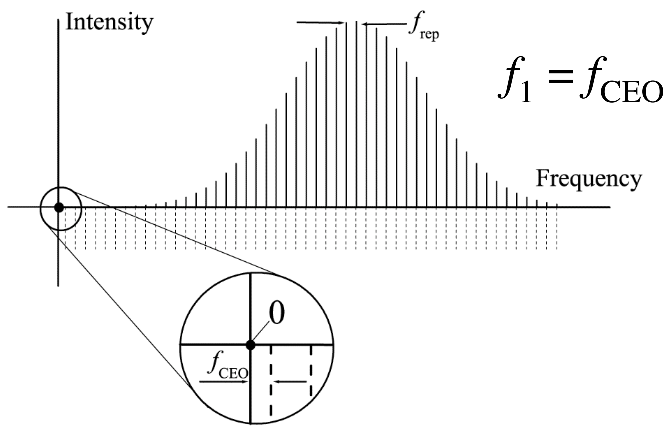
- Integration of absorber into gain structure
- Electrical pumping

What is special about ultrafast solid-state lasers?

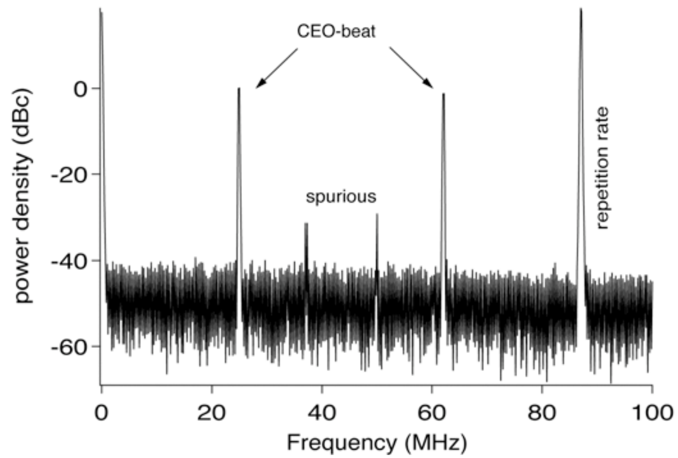




- **World record results in ultrashort pulse generation:** two-optical-cycle regime (≈5 fs) using KLM and chirped mirrors, *Science* **286**, 1507, 1999
- **Carrier envelope offset (CEO) control and stabilization using frequency combs:** *Appl. Phys. B* **69**, 327, 1999 and *IEEE JSTQE* **9**. 1030. 2003

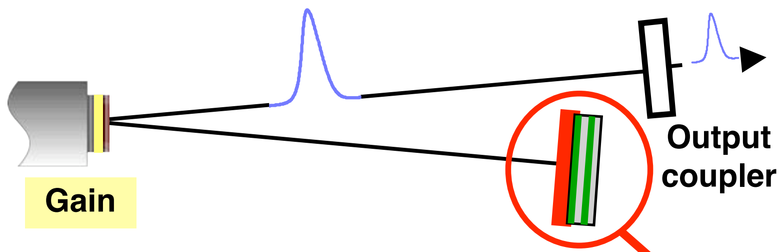


$$f_1 = f_{\mathrm{CEO}} + n f_{\mathrm{rep}}$$



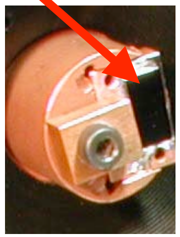
What is special about ultrafast solid-state lasers?

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

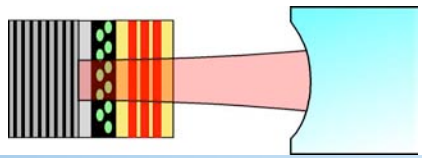


SESAM
SEmiconductor **S**aturable **A**bsorber **M**irror

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



- **Solved Q-switching problem** for passively modelocked diode-pumped solid-state lasers (after more than 25 years) - important for “real-world” applications
- **Pushed pulse energy** of diode-pumped ultrafast solid-state lasers by **four** orders of magnitude: Latest result **11 μJ**, 791 fs, 45 W, 4 MHz
- **Pushed pulse repetition rate** of diode-pumped solid-state lasers by more than two orders of magnitude: **160 GHz** at 1 μm and **77 GHz** at 1.5 μm
- **Passively modelocked vertical external-cavity surface-emitting laser (VECSEL):** for high pulse repetition rates, power scaling to 2.1 W, full wafer-scale integration
  Invited review paper in *Physics Reports* **429**, pp. 67-120, 2006
  MIXSEL - a new class of ultrafast semiconductor lasers



Keller group: Thank you …

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

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

MBE and MOVPE growth in ETH clean room facility (FIRST-lab)
Dr. Matthias Golling
ETH FIRST Lab staff: Dr. Silke Schön (MBE), Dr. Emilio Gini (MOVPE)

High field laser physics, attosecond pulse generation and science
Dr. Lukas Gallmann, Dr. Amelle Zair, Dr. Claudio Cirelli
Christian Erny, Petrissa Eckle, Mirko Holler, Florian Schlapper, Matthias Weger